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Contents

Foreword

The 2023 *Pioneer Research Journal* marks the tenth volume in this annual collection of original undergraduate-level research by young scholars from high schools around the world. The range of research topics naturally change from year to year, but what has remained constant through the ten volumes is the depth of intellectual curiosity that is readily apparent in every research paper featured in the journal.

The scholars whose work is recognized in Volume 10 of *the Pioneer Research Journal* pursue answers to questions ranging from the biological implications of space travel to the furtherance of human rights through the application of Hegelian philosophy. Whether seeking solutions to real-world problems or treading more theoretical terrain, each paper in this volume reflects the deep intellectual passion of its author while demonstrating the commitment to academic rigor expected of every Pioneer scholar.

The essays featured in the pages that follow represent the culmination of the authors' participation in the Pioneer Research Program. In 2023, 1,483 young scholars from 54 countries and regions conducted research through Pioneer Academics, selected from an international pool of 5,229 applicants. Admitted scholars participated in faculty-led, international cohorts before working individually with leading U.S. professors to conduct original undergraduate-level research in their area of interest. After a rigorous nomination and double-blind review process, 30 papers have been selected for publication in this edition of the *Pioneer Research Journal*. The authors herald from high schools in Bulgaria, China, India, Kazakhstan, Singapore, South Korea, and Turkey.

By conducting the guided research entirely online, Pioneer Academics has torn down barriers and made undergraduate-level education available to promising young scholars in virtually every corner of the world. To ensure this opportunity is available to as many students as possible, Pioneer provided approximately US $1.56 million in need-based scholarships, again meeting 100% of demonstrated financial need where need could be assessed and fulfilling its mission to remove obstacles to educational access for the most deserving underserved students.

It is our goal to share this work widely, and so the *Pioneer Research Journal* is available in print and online at www.pioneeracademics.com and is distributed to select colleges, universities, and libraries worldwide.

I am so pleased to share it with you and hope you find it to be inspiring and enlightening.

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Biochemical Properties and Potential Benefits of Creatine as a Dietary Supplement

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1. Introduction

The synthesis of creatine takes place naturally in organs such as the liver, kidney, and pancreas, and creatine's primary storage location is within skeletal muscle. It can be obtained through the consumption of animal-based foods or synthesized naturally within the human body. It plays a vital role in the energy metabolism of most vertebrates by capturing and storing high-energy phosphate groups and donating them to adenosine diphosphate (ADP) to restore depleted adenosine triphosphate (ATP) levels. This reversible process is facilitated by creatine kinase (CK). Following their initial introduction to the general public in the 1990s, creatine supplements have gained significant popularity and are predominantly utilized by athletes as an ergogenic aid (Close et al., 2016). However, whole-body creatine deficiency most strongly affects the nervous system, with the potential to cause cognitive dysfunction, seizures, and behavioral impairments (Mercimek-Andrews & Salomons, 2009). Emerging research has provided evidence of additional positive effects of creatine supplementation on the health of non-athletes, thereby suggesting its potential use for the general public. The purpose of this research paper is to provide an in-depth exploration of the biochemical properties of creatine and its potential as a dietary supplement for the general public. This paper aims to investigate the synthesis, chemical properties, metabolism, and transportation of creatine, as well as its effects on sports performance, cognitive function, and potential applications in cancer treatment and antiviral activity. By reviewing
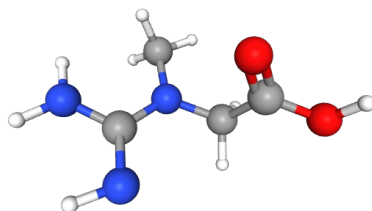
Figure 1. *Creatine 3D structure (PubChem)*

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existing literature and incorporating recent research findings, this paper aims to provide a comprehensive understanding of creatine and its potential benefits for individuals seeking to enhance physical performance, cognitive abilities, and overall health.

2. Chemical Structure

Creatine is a non-proteinogenic amino acid and a glycine derivative with the chemical formula $C_4H_9N_3O_2$. At room temperature, creatine is slightly soluble in water (13 g/L). Like all amino acids, it contains carboxyl and amino functional groups. Due to charge separation and the presence of O-H and N-H bonds, creatine can form hydrogen bonds that play an essential role in protein binding (Colas et al., 2020). The crystal structure of creatine contains hydrogen bonds between guanidine and carboxyl groups as well as charge attraction interactions. The lone pairs on all three nitrogen atoms are delocalized, explaining the trigonal planar geometry on the nitrogen atoms and equal lengths of C-N bonds of the guanidine group. The zwitterionic form is highly stabilized by resonance and is the major species at physiological pH (7.3), with pKa values of amino and carboxylic acid moieties estimated to be 12.7 and 3.8, respectively (PubChem). Owing to charge separation, creatine is a relatively reactive molecule.

Figure 2. *Creatine bond angles and lengths (Arlin et al., 2014) in Mercury (Macrae et al.,*

Figure 3. *Creatine crystal structure (Arlin et al., 2014) in Mercury (Macrae et al., 2020)*

3. Biosynthesis

Figure 4. *Creatine biosynthesis pathway*

Creatine is naturally synthesized in the kidney and liver through the conversion of glycine and arginine, facilitated by the enzyme arginine:glycine amidinotransferase (AGAT). Guanidinoacetate (GAA), formed from the reaction between glycine and arginine, is then methylated by guanidinoacetate N-methyltransferase (GAMT), using S-adenosyl methionine (SAM) as the methyl donor. The result is creatine. Creatine's cyclic form, creatinine, exists in equilibrium with its tautomer and creatine itself (Joncquel-Chevalier Curt et al., 2015).
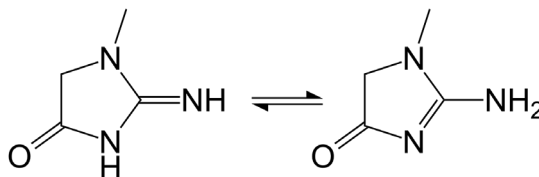
Figure 5. *Creatinine tautomerization*

4. Transportation and Transporter Protein Binding

Creatine is transported through the bloodstream and taken up into the cell by the transmembrane protein creatine transporter, CreaT. Malfunctions or mutations of CreaT can result in creatine deficiency within the brain. Such a deficiency has the potential to cause extreme neurological disorders such as epilepsy and intellectual disability (Passi et al., 2022). CreaT belongs to the solute carrier transporter 6 family (SLC6), specifically the subgroup of GABA transporters (GATs). These transporters, including CreaT, are considered symporters as they transport Na^+ ions along with their respective substrates in the same direction, utilizing the electrical potential gradient across the cellular membrane.

Colas and fellow researchers created homology models of CreaT based on the structurally similar serotonin transporter (hSERT) that shed light on the structural factors characterizing ligand binding to the active site of CreaT. One discovered feature is that transmembrane helix 10 (TM10) has a π helix that provides a specific conformation to the binding site and is believed to influence the substrate selectivity among proteins in the SLC6 family. Another feature is the deprotonated cysteine (C144), located on TM3, that is specific to CreaT. This cysteine plays an essential role in CreaT ligand binding because it allows for S-H-N hydrogen bonding with the guanidine group of the substrate. Complexes of CreaT with different ligands were studied, and it was revealed that optimal binding occurs when the distance between carboxylate and guanidine groups is approximately 4.5 – 5 Å, which corresponds to a linker with 2-3 carbon atoms (Colas et al., 2020).
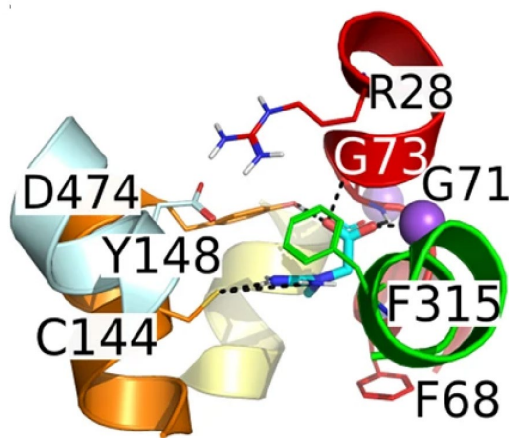
Figure 6. *Creatine binding to CreaT (Colas et al., 2020)*

5. Metabolic Role

About two-thirds of the total creatine in the body is stored in the form of phosphocreatine (PCr). PCr is created by creatine phosphorylation catalyzed by CK and serves as an energy buffer in skeletal muscles and the brain by supplying high-energy phosphates to convert ADP to ATP when needed. The enzymatic breakdown of PCr into Cr and inorganic phosphate (Pi) provides energy that is used to synthesize ATP from ADP and Pi.

Maintaining adequate ATP availability is crucial in situations where ATP levels have been depleted due to high energy demands. The capacity to restore depleted ATP levels assumes significance in sustaining optimal ATP availability. Approximately 95% of creatine is stored in skeletal muscle, with the remaining 5% distributed among other tissues, notably the brain (Balsom et al., 1994). The breakdown of creatine into creatinine occurs at a rate of approximately 1-2% per day. The degradation process is more pronounced in more physically active individuals, as well as individuals exhibiting higher lean muscle mass (Hultman et al., 1996). As a result, a person of average size may require a daily intake of 2-3 grams of creatine to maintain normal levels in their muscles. This requirement can vary depending on

factors such as diet, muscle mass, and physical activity levels. Creatine stores in individuals following either a normal omnivorous diet or a vegan diet are usually not saturated. Therefore, to promote overall health, the recommended daily dietary intake of creatine may range from 2 to 4 grams per person (R. B. Kreider et al., 2017; R. B. Kreider & Stout, 2021).
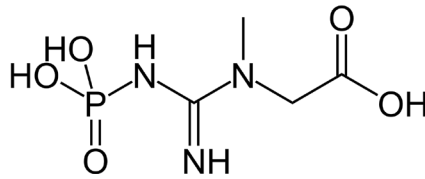
Figure 7. *Phosphocreatine structure*

6. Effects of Creatine Supplementation on Sports Performance

Improved exercise performance associated with creatine supplementation is caused by an increase in muscle creatine and PCr levels (Buford et al., 2007). Studies have shown that individuals who take creatine experience a performance increase of approximately 10-20% in various high-intensity activities, including fitness and weight training (Izquierdo et al., 2002; R. Kreider et al., 1998; Wiroth et al., 2001). These benefits have been observed in both men and women across different age groups. Consequently, it is widely acknowledged among scientists that creatine supplementation is an important and valuable ergogenic aid for athletes. The quickest and most effective way to elevate muscle creatine levels is to consume 5 g of creatine four times a day for 5-7 days (R. B. Kreider & Stout, 2021).

7. Effects on Cognitive Function

The brain is an organ with a high energy demand, which implies that creatine may offer potential cognitive benefits. Indeed, creatine supplementation boosts brain bioenergetics and reduces mental fatigue (Braissant et al., 2011). It has also been observed to enhance extended cognitive abilities in healthy individuals (Van Cutsem et al., 2020) and alleviate the decline in skill execution that arises from lack of sleep (Cook et al., 2011).

8. Creatine's Role in Cancer

Creatine plays a complex role in the development and progression of cancer, because its benefits can be used by both tumor cells and healthy cells. It has demonstrated potential anti-cancer effects, acting as a power source for T cell activities (Campos-Ferraz et al., 2016; Di Biase et al., 2019) and similar effects have been observed with cyclocreatine (Miller et al., 1993). However, recent studies have unveiled the protumor effects of creatine, specifically in promoting cancer metastasis (Papalazarou et al., 2020; Zhang et al., 2021). Additionally, elevated levels of CK have been observed in certain cancers, such as lung cancer (Gazdar & et al., 1981) and

prostate carcinoma (Feld & Witte, 1977). Inhibition of the SLC6A8 gene, responsible for creatine transport, has been shown to reduce PCr and ATP levels in cells and induce tumor apoptosis (Kurth et al., 2021). Despite ongoing research, the complete understanding of creatine's role in cancer remains elusive. Therefore, caution is advised when considering creatine supplementation in the context of cancer.

9. Antiviral Properties: Computational Study of Creatine Binding to SARS-CoV-2 Main Protease

Calculations were performed using (1) the Main Protease crystal structure coordinates as obtained from the Protein Data Bank (PDB) with PDBID: 6Y84 (Owen et al., 2023) and (2) the creatine crystal structure atomic coordinates downloaded from the Cambridge crystallographic database (CSD) CSD code: JOHJIB01 (Arlin et al., 2014). We used software from Biovia (Dassault Systèmes, San Diego, CA, USA). Docking studies were performed with the CDOCKER package in Discovery Studio 2020 version (Wu et al., 2003). Standard dynamics cascade protocol in Discovery Studio
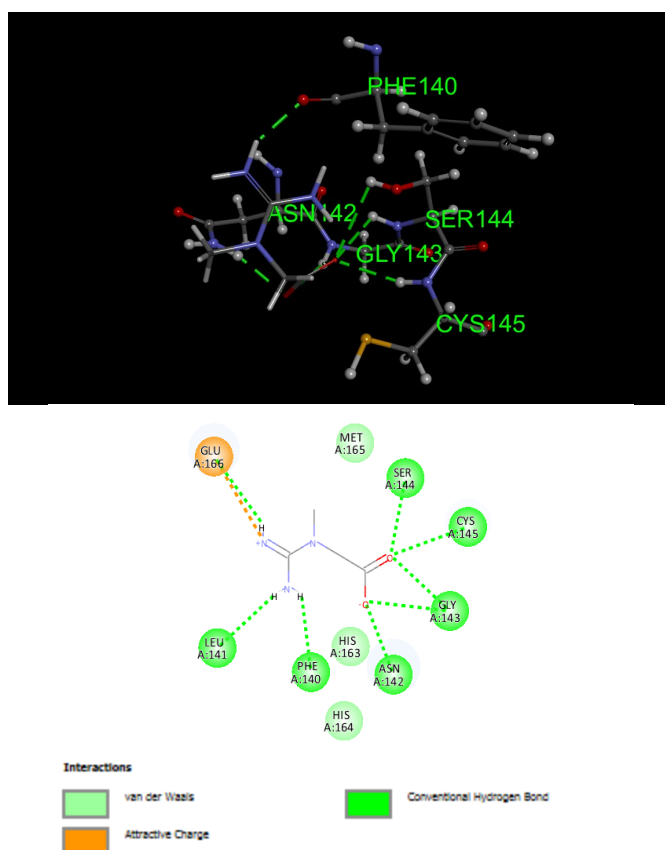
Figure 8. *Creatine binding to SARS-CoV-2 main protease active site amino acids*

allows optimization of atomic coordinates and was also applied to the selected poses.

This computational analysis uncovers the potential of creatine to intricately bind to the active site of SARS-CoV-2 main protease, suggesting its capacity as an inhibitor of this protease, which is known to play an essential role in viral replication by cleaving polyproteins to form multiple functional proteins, including those responsible for RNA replication (Qiao et al., 2021). Additionally, creatine has the potential to prevent the protease from dimerizing, which is necessary for its function. Despite the study's reliance on computational analysis, these findings pave the way for the exploration of creatine as a promising candidate for effectively targeting and inhibiting the protease and therefore the activity of the virus.

10. Interactions with Other Substances

Research indicates a potential exacerbation of liver damage caused by ethanol when taken together with creatine (Marinello et al., 2019). Despite previous suppositions, research has shown that neither anhydrous caffeine nor coffee hinders the performance boost from creatine, but simultaneous ingestion may cause digestive discomfort (Trexler et al., 2016).

11. Safety and Side Effects

Creatine monohydrate (CM) supplementation has been associated with anecdotal claims of side effects such as cramping or fluid balance disruption, but scientific research suggests that these concerns are largely unfounded (Dalbo et al., 2008; Lopez et al., 2009). In fact, Greenwood and others discovered that football players who supplemented with creatine experienced significantly less cramping, dehydration, muscle tightness and strains during training (Greenwood et al., 2003). Creatine has also been speculated to have a negative effect on kidney function. Certain fears about creatine and renal function stemmed from a case study involving a man with pre-existing kidney disease (Koshy et al., 1999; Pritchard & Kalra, 1998). Some concerns have centered around increased serum creatinine levels, which are often used as an indicator of kidney health. However, large-sample studies conducted over several years have not found any significant side effects, including adverse effects on renal function, resulting from CM supplementation in healthy athletes (Groeneveld et al., 2005; R. B. Kreider et al., 2003; Lugaresi et al., 2013; Poortmans & Francaux, 1999). To conclude, current evidence suggests that CM supplementation is safe within recommended guidelines.

12. Conclusion

In conclusion, creatine supplementation offers various benefits in terms of sports performance enhancement, cognitive function improvement, and potential anticancer properties without any known adverse side effects. Furthermore, our computational study reveals creatine's potential as an antiviral agent that arises from its ability to bind to the SARS-CoV-2 main protease. Creatine's wide availability and relatively low cost make it an intriguing research target to investigate as a SARS-CoV-2 treatment. While further research is needed to explore its full range of applications and mechanisms of action, the current evidence supports the use of creatine as a valuable nutritional supplement for both athletes and the general population.

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Navigating the Chaos: Scientific Advancement and War in the Seventeenth Century

Chase Teichholz

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Introduction

The seventeenth century proved to be an eventful time for militaries, with the Thirty Years' War (1618 – 1648) being the most recognized conflict of the era. Originating as an uprising in Bohemia involving the extension of power from the Holy Roman Empire, several opportunistic countries and individuals capitalized on the chaos that ensued. What resulted was a persistent war that saw the Austrian Hapsburgs, the Danish, Dutch, French, Swedish, and Spanish, among others, as the main combatants in a series of prolonged invasions.[1] Staunch religious differences made the Dutch Calvinists detest the Catholic Spaniards. Shifting power dynamics also contributed to the animosity, as Spain had long existed as an unquestioned power in Western Europe. Meanwhile, the French continued to assert their dominance, engaging in a struggle to claim the throne as the preeminent empire further fueling the flames of war.

These military conflicts left a long-standing impact on the evolution of scientific discovery. The hostilities of this period resulted in expansive development in physics and mathematics, especially pertaining to ballistics and projectiles. The constant warfare launched a military revolution. As technology evolved and the landscape of the war increased, each military unit adjusted its strategy, tactics, and size. For example, the infantry units became smaller – a way to promote efficiency and flexibility. As a result, defensive troops were able to mobilize faster, a critical advancement towards combating the new type of artillery developed during the war. Additionally, smaller units meant there were more officers per squad. Fewer soldiers also allowed for better training and mastery of drills, another change attributed to the greater responsibility of each soldier to deliver calculations for artillery and efficient defensive positioning.[2]

This paper will evaluate how military strategy and sentiment throughout the Scientific Revolution directly impacted Galilean and Cartesian innovation.

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[1] Myron P. Gutmann, "The Origins of the Thirty Years' War," *The Journal of Interdisciplinary History*, vol. 18, no. 4, 1988, pp. 749–770.

[2] David A. Parrott, "Strategy and Tactics in the Thirty Years' War: The 'Military Revolution'," *The Military Revolution Debate*, 2018, pp. 227–252.

Previous scholarship tends to focus on analyzing their discoveries and the methodologies behind them, disregarding just how the two were informed by their pasts. Traditional thinking recognizes the impact of context and experience in shaping beliefs. However, as it pertains to scientific findings, previous works have not adequately explored this idea relating to Descartes and Galileo.

Both Galileo Galilei (1564 – 1642) and René Descartes (1596 – 1650) were involved in war in some respect, with Descartes serving as a volunteer fighter and military engineer, and Galileo using the state of affairs and existing warfare to drive his theories. In their respective ways, each figure was profoundly affected by the military and the surrounding conflict.

Existing historiography has considered a connection between Descartes and Galileo, establishing how the former reacted to Galileo's conviction. Certain scholars have explored their relationship in terms of Copernican heliocentrism and "the Metaphysical Foundations of Physics."[3] The connection between the natural philosophers and surrounding conflict is not a focus of the analysis of previous scholars, but it is important in linking the two men.

Given just how expansive the Thirty Years' War proved to be, and how long the other conflicts of the time endured, war touched the lives of many. For some, like Descartes, it served as the impetus, perhaps inspiration, for his ideology. For others, like Galileo, it seeped into their thinking, existing more as a context in which to base or formulate ideas. Galileo and Descartes are case studies of the ways in which war can cultivate innovation and breed creativity. Each of these intellectual giants was impacted by the war differently and left the world with equally important ideas.

Innovation Through Conflict: Galileo

Galileo's work is some of the most scrutinized and written about in the scientific field. His discoveries paved the way for a new age, as he questioned and debunked the Aristotelian notions of physics. Many scholars extensively discuss the ramifications of these findings, which, deservedly so, have garnered tremendous attention. However, they have not focused on his relationship with conflict.

In the theaters of war surrounding him, Galileo Galilei forged a path, as any inventor would, to further his discoveries, harnessing the brutal conflict around him to inspire and advance his thinking. While he was never a soldier, global conflict led him to invent, refine, and perfect. He understood the chaos that engulfed him, using his surroundings as fuel and evidence to formulate, and better, his discoveries.

This correlation is best evidenced by one of his most well-known works, *Operations of the Geometric and Military Compass* (1606), which directly connected to the theme of war. In his *Operations*, Galileo clearly correlated scientific discovery and precision with warfare. He linked gunners' calibration to angles of cannonball fire as a method for determining the most efficient artillery positioning given the weight of a lead ball. Through a standardized equation, Galileo insisted that "those lines will serve us for exact calibration," which, along

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[3] Michael Friedman, "Descartes and Galileo: Copernicanism and The Metaphysical Foundations of Physics," *A Companion to Descartes*, Edited by Janet Broughton and John Carriero, Malden: MA, 2008, pp. 69–83.

with "the diameter of the mouth of any artillery piece," gave a finite weight of the ball that cannon could carry.[4]

It is important to note the context in which Galileo pursued battlefield mechanics. His fields of study, namely ballistics and projectiles, were not only valued by his predecessors but followed the traditions of Italian philosophers and mathematicians. He was essentially a third-generation observer of projectile motion, with his most prominent inspiration being Nicolò Tartaglia (1500 – 1557). Like Galileo, Tartaglia had an obsession with ballistics and sought to redefine science through concrete deductive reasoning and thorough mathematics.[5] Existing scholarship has considered Galileo in this context as the next great in a lineage of Italian philosophers. It evaluates him as a leading contributor to an elaborate tapestry of innovative ideas stemming from the Scientific Revolution. This analysis leaves out several other factors that informed Galilean ideas but is not inaccurate in connecting him to the likes of Tartaglia.

While Tartaglia did not initially intend to concentrate on battlefield projectiles, it must have certainly crossed his mind when a friend approached him about calculating the proper angles at which to fire a cannon. In his *Two New Sciences* (1638), Galileo would address this same quandary, pertaining to cannon fire and artillery motion, nearly thirty years later. Galileo's findings corroborated Tartaglia's and offered the word "*parabola*" as an explanation for the curved motion Tartaglia had observed. When discussing the motion relative to a prism, Galileo elaborated on the force and resistance in motion, claiming that, "this parabolic solid is equally strong throughout."[6]

Long before *Two New Sciences* or even *Operations*, Galileo had been sought after by Venetian leadership in an effort to improve their naval engineering and ship construction. While the Venetian Empire, which functioned as a republic, was not a primary actor in the Thirty Years' War, Venice had engaged in a series of battles, most notably in the Ottoman-Venetian wars, spanning from the late fourteenth century to 1718. Specifically, the Battle of Lepanto (1571), a culminating moment in the aforementioned conflict, saw the Venetians and Turks engaged in a grand naval spectacle the likes of which would not occur again until the Spanish Armada in 1588. The Venetians and their allies emerged victorious, and while an end to war never presented itself, the Venetians celebrated a crucial win.[7] Nonetheless, the confrontation featured galleys and armed arsenals; it left a plethora of opportunities for technological and strategic advancement.

Despite this victory, the following decades left Venice a dwindling empire. A series of peace negotiations pushed the Venetians into a partial demobilization, which made them vulnerable and more concerned with maintaining their territory. The prolonged conflict occupied the time and resources of the Venetian Republic, which, in defending itself from Ottoman

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[4] Galileo Galilei, *Operations of the Geometric and Military Compass*, Translated by Stillman Drake, Washington D.C.: Smithsonian Institution Press, 1978. p. 21.

[5] Matteo Valleriani, *Metallurgy, Ballistics and Epistemic Instruments: The Nova Scientia of Nicolò Tartaglia – A New Edition*, Berlin: Max Planck Research Library, 2013. https://edition-open-sources.org/author/22.html.

[6] Galileo Galilei, *Two New Sciences*, Translated by Henry Crew and Alfonso de Salvio, New York: The Macmillan Company, 1914, p. 144.

[7] Michael Edward Mallett and J.R. Hale, *The Military Organization of a Renaissance State: Venice, c. 1400 to 1617*, Cambridge: Cambridge University Press, 2006, p. 239.

expansion, focused extensively on military strategy and the overall theme of war. Additionally, Venice's involvement in conflict increased the state's interest in fostering greater advancement in military science.[8]

That setting impacted Galileo tremendously. He would converse with Venetian leadership on numerous occasions, one being an exchange in 1593 in which he assessed and critiqued the position and strength of the Venetian galley, a ship propelled by oars, identifying the central problem: a faulty lever. While Galileo's proposed solution never came to fruition, as it made the oarsman work significantly harder for a slightly better result, this episode helps to define an established relationship between the scientist and the Venetian Arsenal.[9] Conversely, Galileo learned from the military, adopting the idea for larger and updated ships from engagements with naval leadership, and innovating to make it happen.[10]

Despite these infrequent interactions, Galileo was not directly involved in war.[11] As a result, Galileo the strategist was not a tangible reality. He was not involved in the day-to-day structure or development of military tactics, and hence, was not a military mind. The Galileo that published *Two New Sciences* had already undergone the trials and tribulations of his conviction of suspected heresy, and thus, had largely abandoned projects relating to heliocentrism. Accordingly, continuing Tartaglia's work served as a less controversial way for Galileo to innovate scientifically within the confines of his social sphere, avoiding further retribution from the Church. Beyond that, advancing the work of projectiles and ballistics was a lifelong passion, a way to further explain the perfection of nature, and to do so through mathematics.[12] Galileo had always desired to break the limits of the old scientific world, partially tear up the Euclidean methods and start graphing the curves experienced by objects in motion. Whatever its involvement in the aforementioned war was, Venice served as a tremendous playground for Galileo to develop this interest in military science.

In fact, his experiences in Venice, including its involvement in a war with the Ottomans, forged the connection between war and his science. Venice, as a place renowned for military science, helped plant the seed that future conflicts, notably the Thirty Years' War, would help sprout and bloom. As a result, when Galileo wrote *Two New Sciences*, in which he added to Tartaglia's discoveries, he placed his dialogue in Venice, despite living in Florence under house arrest and not having been to Venice since 1610. In fact, during the publication process,

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[8] Mallett and Hale, *The Military Organization*, p. 240.

[9] Domenico Bertoloni Meli, *Thinking with Objects: The Transformation of Mechanics in the Seventeenth Century*. Baltimore: Johns Hopkins University Press, 2009.

[10] Meli, *Thinking with Objects*, p. 68.

[11] Still, the war was not too distant either. The struggles of Galileo's relatives guaranteed that the war touched him in some capacity. His family, specifically his brother Michelangelo, was affected by the recent war. With their home destroyed, they were forced to become refugees. Furthermore, Michelangelo's decision to pursue music created a financial burden on his brother, the inventor. As a result, prior to his persecution and subsequent trial, Galileo undertook certain projects with more monetary aspirations. Speculation from less reliable sources, including websites focused on military news, has dubbed Galileo a military contractor, a hypothesis likely grounded in this notion. See website, *We Are The Mighty*, run by veterans, that named Galileo "one of the world's first defense contractors." However, despite his consultations in Venice, there is no substantial evidence that characterizes Galileo in that light.

[12] David Wootton, *Galileo: Watcher of the Skies*, New Haven: Yale University Press, 2013, p. 12.

Galileo aspired to first release it in Venice, and did not make any specific mention of Florence.[13] Using Venice, a naval power with a rich military background as the setting for his work, rather than the home of the more conciliatory Florentines, Galileo focused his discoveries on the militaristic applications.

Perhaps his work would not spark revolutionary change within the conflict, but the pervasiveness of the Thirty Years' War made war a constant for everyone. Therefore, Galileo used military personnel and equipment as examples and objects with which to examine the motion of projectiles. Through the military lens, the impact of the Thirty Years' War, and war at large on Galileo is apparent; it provided him with a context for his discoveries and fostered more expansive innovation in battlefield mechanics and ballistics.

However, as described above, much before the onset of the Thirty Years' War, Galileo had taken a genuine interest in advancing military technology. The most prominent demonstration of this passion was the construction of the military compass. Though it was not crafted as a naval device, Galileo recognized that application immediately. Interestingly, when he discussed the use of the compass with the Florentine leadership, he never mentioned its military capabilities. Conversely, when he presented his finalized and perfected compass to the royalty of Venice, he emphasized its naval and navigational advantages to Venetian leadership.[14] He described it as a device meant for measuring distance. However, he emphasized that "the telescope has the advantage of discovering the ships of the enemy two hours before they can be seen with the natural vision."[15] He touted the specific characteristics, quality and quantity of ship, and formation that the telescope identifies, further conveying the military applications of his device. Furthermore, Galileo promised to keep the invention "a great secret" and reveal it only to the Venetians, a demonstration of loyalty as well as his affinity for Venice. The naval advantages of Galileo's compass certainly highlight the lens in which he evaluated certain scientific problems, even before the Thirty Years' War.

Galileo's expansive connections between war and scientific achievement were not limited to the compass, as he had deliberated on the composition of Venetian ships, and how improving them could reap benefits. In fact, his interest is evidenced by his attempts to write what would become his *Two New Sciences*. He had contemplated working on it since 1609 but failed to return to the subject until the onset of war. The telescope helped halt additional military mechanic studies, as its broader impact on the world and tragic personal tribulations shifted Galileo's focus to other endeavors. The telescope would pit Galileo against the conventional logic of the Catholic Church, leading to a trial and his conviction. After his trial, Galileo found time to return to the ambitious work of his predecessors and provide a revamped, updated version of their studies in the publication of his own experimental physics and mechanics.

Despite the passion burning within the now grizzled, humbled Italian philosopher, which manifested itself in a planned exploration, Galileo struggled to finish the piece. Luckily, though, war produces and reveals problems that

[13] Wootton, *Watcher of the Skies*, p. 229.
[14] Mario Biagioli, "Galileo the Emblem Maker," *Isis*, vol. 81, no. 2, 1990, pp. 230–258.
[15] Galileo Galilei, "The Uses of the Telescope, 1609-10," The University of Michigan Library, www.cabinet.ox.ac.uk/uses-telescope-1609-10.

require practical solutions. The project would do more than fulfill his personal ambitions. The war-stricken society presented an opportunity to penetrate the barriers of projectiles in a time where that knowledge could ensure victory or defeat.

Many scholars have explored how Galileo's past, especially his interest in previous work relating to ballistics, led to certain inventions, such as the telescope. In that context, his *Two New Sciences* served as a continuation of Tartaglia's work, among others. However, the constant backdrop of warfare, a concept not highlighted in previous scholarship, impacted his mindset and the expression of his contributions to the field of his predecessors.

Galileo's *Two New Sciences* represents the culmination of that decades-long interest, resulting from Galileo's expansion of Tartaglia's experiments nearly thirty years after professing his interest in the subject. Specifically, in *Two New Sciences*, Galileo explores the speed of light, trying to conceptualize how people could tangibly view a massless form of energy. He describes the light as "instantaneous," using specific real-world ideas to corroborate that explanation.

> When we see a piece of artillery fired, at great distance, the flash reaches our eyes without lapse of time; but the sound reaches the ear only after a noticeable interval.[16]

Through this application, the artillery operates as the center of the experiment, helping determine that, while sound travels with some delay, light is different; the visible reaction is immediate. Clearly, the subject matter need not directly apply to warfare. There could easily have been a hypothetical discussion that analyzed results from other thought experiments. Galileo, however, chose this specific context as the vehicle for his idea. Though the war was not on his doorstep, Galileo's decision indicates that the notion of global conflict influenced his overall thinking process. War and physics are intrinsically linked and returning to ballistics in a time of war conveys that recognition of the greater world around him.

Similarly, when evaluating the parabolic motion of objects released in free-fall from identical heights, Galileo selected a cannon ball and a musket ball as items for the study:

> But I who have made the test can assure you that a cannon ball weighing one or two hundred pounds, or even more, will not reach the ground by as much as a span ahead of a musket ball weighing only half a pound, provided both are dropped from [the same] height.[17]

Accessing cannonballs for observation might prove troubling in most places. Venice made that task fairly easy. This thought experiment serves to further illuminate why Galileo set his final work in Venice. In Venice, he had experienced the military and naval conflict firsthand, observed active military personnel, and even consulted leaders about improving certain ship technologies.

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[16] Galilei, *Two New Sciences*, p. 42.
[17] Galilei, *Two New Sciences*, p. 62.

Logically, even after having left the city many years earlier, Venice was clearly the sensible setting for his *Two New Sciences*.

In another instance, Galileo conducted experiments around hypothetical certainties surrounding the composition of Earth and set his hypotheses in the context of the battlefield. This marked the persistent and strong impact of the war and how he consistently rooted his ideas in that context. Galileo's later life was enveloped in this great theater of war, and accordingly, his studies and abstractions are as well.

Galileo's reaction to his surroundings cannot all be attributed to one factor. Scholarship on Galileo focuses largely on his relationship to the Church, his trial and conviction, and their impact on his discoveries. The implications of that experience have been explored extensively, both as it pertains to Copernican heliocentrism and the future of astronomy. However, the generational context also contributes to understanding how he processed the war. As demonstrated by his desire to continue the studies of Tartaglia and the tradition of Italian scientific philosophy, Galileo valued the old way. Still, he did hope to eliminate the more outdated methods associated mainly with Euclid. While more likely his desire to pursue accuracy than to discard traditional thinking, there is no denying Galileo's ambition to provide the most updated framework.

Galileo spoke extremely highly of those before him, most notably Copernicus and Archimedes. Despite disagreeing with mathematicians like Euclid, they still influenced the foundation of the science with which he worked. He adopted some of their techniques and tactics for his *Two New Sciences* and stopped short of dismantling the entire status quo. As much as Tartaglia directly impacted ballistics and Galileo's passion for the field, Galileo evaluated the speed of light or the physics of free-falling objects through a combination of lenses: seeing is believing and sight serves as the most definitive vehicle for understanding; conversely, he understood that not everything is in plain sight.[18] Essentially, Galileo infused Euclidean notions with Aristotelian ones, respecting and honoring traditional thinking while adding to the depth and reliability of scientific information.[19] A great deal of innovation followed, as Galileo and Tartaglia had to radically alter the applications of certain methods.[20] In this way, while staying true to convention, Galileo found space to cultivate new knowledge.

In essence, Galileo's later works are new chapters in a rich area, cultivated and studied by generations of Italian scientists. In naming the "parabola" and diving into projectile motion, Galileo contributed to the world of military science that had been constantly evolving for decades. Rather than be molded by the war, though that certainly plays a role, Galileo returned to what initially sparked his interest – the discoveries of old – and refined them into more contemporary forms.

The work of the Marquis Guidobaldo dal Monte, one of Galileo's friends and colleagues, further highlights the overall impact of the war on science in this period.[21] The title page of his book included a dedication devoted to praising

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[18] Wootton, *Watcher of the Skies*, p. 253.
[19] Wootton, *Watcher of the Skies*, p. 253.
[20] Mary Henninger-Voss, "How the "New Science" of Cannons Shook Up the Aristotelian Cosmos," *Journal of the History of Ideas*, vol. 63, no. 3, 2002, pp. 371–397.
[21] Meli, *Thinking with Objects*, p. 19.

military men, implying that the book, about science, provided valuable insights to commanders:

> To the benefit of those who find pleasure in this most noble science, especially war captains, engineers, architects, and all sorts of artificers who intend to perform wonderful and almost supernatural works, by means of machines.[22]

In this context, Galileo's decision and motivation to complete *Two New Sciences* during this period becomes clearer; as does the impact that the context of war, particularly in Venice, had on his work. The worlds he inhabited, especially Venice, have historically been considered, but often as mere biographical context. Instead, Galileo's implementation of war material and strategy signifies a marked connection between his experiences living there and how he expressed his findings.

The backdrop of war, in both the global context and that of Venice, clearly impacted Galileo's studies. As evidenced by the militaristic lens in *Two New Sciences* as well as the applications of his compass and connection to the Arsenal, Galileo not only lived through wars, but inserted himself into them. Galileo's handling of the war-torn world around him represents the impact war can have on science: pushing it forward, accelerating related findings, and fostering developments that contribute to faster victory and subsequently, lasting peace.

The Military Mind: Descartes

René Descartes' more direct brushes with war fostered a perspective that shaped his understanding of the world around him. He operated within the context of the Thirty Years' War as a soldier, solidifying his "military mind." Descartes fancied himself a scholar of military strategy, and, as his biographer noted shortly after his death, he "made it his business to understand Military Discipline among the Hollanders."[23] He chose not to enlist and avoided "public command" in an effort to "perform the duty of a private soldier." He served in the forces of the Dutch Republic under Prince Maurits, known as Maurice of Nassau (1567 – 1625). While Descartes himself rarely detailed his military endeavors, biographers and historians have delivered accounts, portraying Descartes as having a nuanced understanding of warfare and strategy. In fact, there has been speculation about whether he assumed a more involved role in military service. Scholars have deduced, given his desire for secrecy and certain letter exchanges, that Descartes might have served as a spy during the conflict.[24]

In his numerous experiences in conflict, most notably his voluntary participation in the siege of Breda and the battle of Prague, Descartes formulated

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[22] Mary Henninger-Voss, "Working Machines and Noble Mechanics Article: Guidobaldo Del Monte and the Translation of Knowledge," *Isis*, vol. 91, no. 2, 2000, pp. 233–259.

[23] Peter Borellus, "The Life of Renatus Descartes," *A Summary or Compendium of the Life of the Most Famous Philosopher Renatus Descartes Written Originally in Latin by Peter Borellus*, 1670, pp. 7–8.

[24] Harold J. Cook, *The Young Descartes: Nobility, Rumor, and War*. Chicago: The University of Chicago Press, 2018, pp. 24–27.

his beliefs.[25] Through the lens of a frontline soldier, military engineer, and strategist, Descartes cultivated order in the chaos, creating a cohesive, structured, and rigid view of the world to combat the disorder of war. This concept grounds Cartesian logic and ideology in the context in which its creator originated. However, Descartes was not affected solely by the extensive conflict surrounding him. In fact, he was impacted tremendously by the French political sphere through which he traversed during his early years. Existing scholars make little reference to Descartes' connection to the French political world beyond contextual introductory information. As a result, it fails to account for this connection, one Descartes himself recognized. He pondered the extent to which his time in France, and the political turmoil there, changed his beliefs.

> I had recognized in my travels that all those who have sentiments quite contrary to our own are not for that reason barbarians or savages, but that many of them use their reason as much as or more than we do. And I considered how one and the same man with the very same mind, were he brought up from infancy among the French or the Germans, would become different from what he would be had he always lived among the Chinese or the cannibals, and how, even down to the styles of our clothing, the same thing that pleased us ten years ago, and that perhaps will again please us ten years hence, now seems to us extravagant and ridiculous. Thus it is more custom and example that persuades us than any certain knowledge; and yet the majority opinion is worthless as a proof of truths that are at all difficult to discover, since it is much more likely that one man would have found them than a whole multitude of people. Hence I could not choose anyone whose opinions seemed to me should be preferred over those of the others, and I found myself, as it were, constrained to try to guide myself on my own.[26]

Given Descartes' reservation to speak about his past, likely attributed to his appreciation of secrecy and the tumult of his time, he rarely spoke of his involvement in France. However, he acknowledges the impact of one's upbringing and experiences in shaping their perspective. Applying this belief to himself, Descartes' motives, opinions, and theories all stemmed, at least in part, from the situations he encountered in the French political sphere.

As far as his specific dealings in that world, Descartes aligned with King Henri IV (1553 – 1610), the French ruler for more than two decades. He would attend Henri's funeral proceedings even after largely disassociating from France.[27] Following Descartes' eventual demise, his final resting place resembled Henri's, with similar structural composition. Biographers have suspected this to represent a long-standing respect between the scientist and the king. Part of their connection rested in a common belief in politique: a thought process prioritizing the rule of law over individual power. Even in this connection, the emphasis on order and structure is apparent. Descartes even attended a Jesuit college founded

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[25] Borellus, *The Life of Descartes*, p. 8.
[26] René Descartes, *Discourse on Method*, Translated by Laurence J. Lafleur, Indianapolis: Bobbs-Merril Educational Pub., 1980, p. 16.
[27] Cook, *The Young Descartes*, p. 42.

two years prior by Henri IV, a symbol of reconciliation between the Jesuits and the French throne.[28]

Before leaving his ambitions in France behind, Descartes returned to France in 1614 in an attempt to obtain political office, following in his father's footsteps. Joachim Descartes (1563 – 1640) served as a judge during the trial of nobles and maintained a relationship with the cardinal.[29] Conversely, Descartes associated with a crowd that opposed the cardinal, and Descartes was in all likeliness not a staunch supporter of the religious figure.

The French political system was extremely corrupt:

> Religious wars and the struggle against Hapsburg power siphoned away much of the Crown's political and financial capital. When strong leadership finally emerged, briefly under Henry IV and then under Cardinal Richelieu, the legal system was more often manipulated by the Crown for political and financial objectives than strengthened and reformed as a system of litigation and law enforcement.

> The failure of the royal government to deal with judicial corruption and abuses of venality [led] to an increasingly cumbersome and ineffective legal bureaucracy.[30]

Beyond the conflict, the chaos in France caused Descartes not only to distance himself from the country, but further contributed to his logical, rigid, and ordered societal views. To be fair, his experiences in this political world are only part of the picture. Explorations of Cartesian ideology, both its focus and its reasoning, incorporate his education at La Flèche. As a student, he became engrossed with the "certainty" and "self-evidence" of mathematics.[31] These explorations into Descartes' works tend to emphasize practical and logical analysis of his findings. Thus, the connection between Descartes' service and involvement in the French political scene is either overlooked or not materially considered in relation to his tangible discoveries. However, Descartes' priorities and thinking are connected to his past. In his *Discourse on Method*, in which he provides a framework for how to solve complex problems, Descartes speaks to this analytical, logic-based format.

> The third was to conduct my thoughts in a given order, beginning with the *simplest* and most easily understood objects, and gradually ascending, as it were step by step, to the knowledge of the most complex;

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[28] Desmond M. Clarke, *Descartes: A Biography*, Cambridge: Cambridge University Press, 2012, pp. 15–17.
[29] Cook, *The Young Descartes*, pp. 43–44.
[30] Jeffrey K. Sawyer, "Judicial Corruption and Legal Reform in Early Seventeenth-Century France," *Law and History Review*, vol. 6, no. 1, 1988, pp. 95–117.
[31] Mary Domski, "Descartes' Mathematics," *The Stanford Encyclopedia of Philosophy* (Fall 2022 Edition), Zalta, Edward N. and Nodelman, Uri. https://plato.stanford.edu/archives/fall2022/entries/descartes-mathematics.

and positing an order even on those which do not have a natural order of precedence.[32]

As one of his four central principles expressed in *Discourse*, the Cartesian logic exhibited in this rule perfectly encapsulates his overall thinking. There is an inherent logic and common sense in this assertion that simple ideas and problems should be dealt with before handling complex concepts and equations.

Despite the significant impact the French system left on the young mathematician, his life as a soldier, in each of its forms, most directly contributed to the Cartesian ways of thinking. In *Discourse*, Descartes briefly referred to his time in the service.

That is why, as soon as age permitted me to emerge from the supervision of my teachers, I completely abandoned the study of letters. And resolving to search for no knowledge other than what could be found within myself, or else in the great book of the world, I spent the rest of my youth traveling, seeing courts and armies, mingling with people of diverse temperaments and circumstances, gathering various experiences, testing myself in the encounters that fortune offered me, and everywhere engaging in such reflection upon the things that presented themselves that I was able to derive some profit from them.[33]

His writings underscore another component of the Cartesian ideology: people are not different due to varying levels of intellect. Everyone possesses common sense; differing life experiences and interests create diametrically opposite individuals.[34] Descartes' experiences on the battlefield represent a core set of moments that shaped that perspective.

Descartes' involvement in the military was multi-faceted. Each campaign required courtiers, engineers, and actual soldiers. He desired to master the methods and techniques of war in their totality. As a result, when he joined the Dutch armies, he learned military engineering, unlocking his admiration of mathematics. Past analyses merely allude to this phase of Descartes' life, not discussing its effects beyond biographical information. Scholars have correlated, indirectly, his military service with a shift in his mindset, culminating in "a distinctive intellectual trajectory."[35] That relationship, however, is far more extensive and direct. Under the leadership of Maurits van Oranje, the most reputable general and tactician of the era, Descartes obtained real-world experience both in strategy and on the battlefield.

The persistence of war made engineers both necessary and better equipped than ever. War mechanics covered the logistics of sieges and bastions and the positions and applications of pulleys. Whether they involved angles of cannon fire or determining the kinematics of projectiles hurling through the air, all could prove exceptionally important in winning battles. Mobile artillery, another invention of the era, allowed for straightforward bombardment so long

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[32] Descartes, *Discourse on Method*, p. 18.
[33] Descartes, *Discourse on Method*, pp. 5–6.
[34] Cook, *The Young Descartes*, p. 12.
[35] Stephen Gaukroger, "Life and Works," *A Companion to Descartes*, pp. 3–16.

as the cannons were in proper positions. Engineers and mathematicians helped establish where those locations were, which maximized the power of said weaponry. The same applied to defense structure; if cannons could fire at closer ranges, science and math were required to build stronger, more capable walls. In introducing more advanced weapons and consequently, creating more detailed plans of attack, soldiers and engineers alike needed to understand the mechanics of it all including how to operate each device and calculate their positions. Those mathematical decisions often utilized instruments that helped survey the territory and place artillery at angles that would result in damage and success.[36]

Through this technical understanding of warfare, Descartes amassed tremendous respect for the militaristic world view that centered around order and stability. In *Discourse*, he reflected further on the serenity of the order in the service.

> It is eight years ago that this desire made me resolve to take my leave of all those places where I might have acquaintances, and to retire here, to a country where the long duration of the war has led to the establishment of such well-ordered discipline that the armies quartered here seem to serve only to make one enjoy the fruits of peace.[37]

While Descartes did not expand on his military life, he alluded to the admirable qualities of the armies including its capacity to provide that order and discipline that permits, even enhances, peace. Another component of Descartes' appreciation of the military lifestyle, and its positive effects, is secrecy. In addition to presiding over the aforementioned trial, Descartes' father was involved in a spy plot that successfully led to the capture of Spanish espionage agents.[38] While speculation over whether Descartes ever served as a spy continues, he did respond with the tact and privacy required in that role. Descartes once adopted a motto, asserting that, "a life well-hidden is a life well lived," demonstrating a clear affinity for secrecy.

He discussed traveling the world as a form of masking oneself. In a time of division, Descartes saw seclusion and secrecy as a way to harness the chaos and find a safe space to conduct his studies. His description of the land he retired to, not necessarily an isolated location, but one without acquaintances and loved ones, established his priorities. His settlement was a microcosm of his ideology: order over emotion, structure over individuality. That masking might have prevented his greater involvement in political affairs, but more importantly, it speaks to his understanding of the world around him. That secrecy and introspection manifests itself in his decision to leave those acquaintances for the opportunity afforded to him by the military discipline.

The impact of his alleged experiences as a spy on both his life and ideology further elucidates the connection between his philosophy and the war. Descartes' wartime as a military engineer and strategist are not the only components of conflict that influenced him. In a letter written by Descartes to a friend, he explained the thrill of his work, a fascinating tapestry of thought, logic,

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[36] Cook, *The Young Descartes*, p. 82.
[37] Descartes, *Discourse on Method*, p. 18.
[38] Cook, *The Young Descartes*, p. 36.

and mathematics. To Descartes, "the pursuit of true philosophy was a work of valor, or that the struggles by which one arrives at truth are like the battles in war."[39]

Descartes evaluated his own discipline as a conceptual battlefield. He was a military mind. The world manifested itself to him as a game of chess, with pieces and equations moving across the vast landscape of his brain.

Two Different Outcomes: The Divergence

Both Descartes and Galileo engaged in a world that, in some form, was overrun with conflict, strife, death, and destruction. For the former, as a soldier and military engineer, the war was forever burned into his eyes, an experience that would forge his future ruminations. The latter watched as an observer, using that context to revolutionize and update the field of projectile motion. Yet, even in the same backdrop, the two figures did more than approach war differently. Descartes had the luxury of reading *Two New Sciences*, Galileo's final work that succeeded *Discourse* by a year, and was not too fond of the Italian's style.

> His reasons for proving the motion of the earth are good reasons; but it seems to me that he does not set them out as one should in order to persuade, for his digressions cause one to forget the earlier reasons by the time one is reading the later reasons.[40]

Descartes disliked the less structured, more fluid argumentation employed by Galileo. While not unexpected, the above quote illustrates how war led Descartes to that preference. Interestingly, Galileo's style never wavered, as he frequently entertained tangents. This choice is also indicative of Galileo's attitude towards the war, as each idea branches off into more opportunity, much like how he cultivated the wars of his lifetime into advancing a scientific field.

Given its mathematical applications, Galileo's *Two New Sciences* served as necessary reading, highlighting the progression in military science. Even in the scale of one anecdote from Descartes about Galileo, there are clues into how the war, and each one's experience, affected their writing styles and their views of the world. The simplistic, ordered Cartesian methods contrast with the flowing, unpredictable Galilean writings.

Their different ages also contributed to their reactions to the conflict around them. The more youthful Descartes allowed the conflict to vastly impact his life perspective, whereas the older Galileo returned to long-standing tradition in the eye of conflict. He progressed the works of mathematicians who had discovered Archimedes and began calculating the specifics of military ballistics, particularly that of his Italian predecessors who lived in the non-stop theater of war that was Italy. Still, though, the generational divide does provide another lens to evaluate the way each cultivated the world of war around them.

The chief point of divergence lies in their actions within a similar context. Both lived through war, yet neither had the same reaction. Descartes' work as a

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[39] Cook, *The Young Descartes*, p. 4.
[40] René Descartes et al., *Oeuvres de Descartes*, Paris: Editions du Cerf, 1897, p. 305.

soldier led him to create a methodology centered around ideals practiced in the military: order, rigidity, and logic. Galileo's response to the same world was to chart a new chapter in tradition, continuing the work started by Tartaglia. However, Galileo used the war as a vehicle for examining that subject, choosing artillery fire, cannons, and other weaponry to explain the science of projectiles. Additionally, Galileo set his *Two New Sciences* in Venice, despite having left the city a decade before writing it. Venice had engaged in conflict with the Ottomans for a generation and his interactions with naval strategists regarding his compass imply that he benefited from the militaristic uses of his invention. In dealing with conflict, Descartes looked towards the future while Galileo found solace in the past.

Without the war to provoke new thought, Descartes might have remained engulfed in French politics. His service provided an outlet from the chaos, and subsequently, shaped the structure of Cartesian thinking. Instead of bridging his experiences with his perspective on mathematics, existing analysis falls short, declaring his time in the service as formative, but not evaluating it in the context of his ideology. Rather plainly, Descartes "the military mind" is who wrote *Discourse* and *Meditations*; he is the manifestation of the war, a reaction to the military order that contrasted the brutal incoherence of conflict. While the tale is different for Galileo, war still greatly inspired his work.

Using both Descartes and Galileo as case studies for determining how the devastation of war breeds scientific innovation, the impact of conflict becomes ever more apparent. Perhaps their unique responses to a world engulfed in conflict contributes little in evaluating their impact as scientists. Each discovery, advancing mathematics and physics into the studies they are today, maintains the same impact no matter how Descartes and Galileo arrived at them. Nonetheless, exploring the relationship between man and war – one that has evolved through centuries – allows scholars to get into the headspace of the most prominent figures of the past. The ways in which war, directly and indirectly, molded Galileo and Descartes advance the understanding of how conflict affects perspective. Cartesian and Galilean methodologies would be unrecognizable if not for each of their interactions with warfare. Two different reactions to the surrounding conflict resulted in two very contrasting ideological stances.

Historian A.J.P. Taylor once stated, "war has always been the mother of invention."[41] In their own unique methods, Galileo and Descartes navigated their experiences with the inevitable and undefeated construct of war, harnessing it into creation and discovery.

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[41] A.J.P. Taylor, Preface. *The First World War: An Illustrated History*, London: Penguin Books, 1966.

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Associations Between Country-Level Digitization, Formation of Imperfect Markets, and Firm-Level Productivity

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Abstract

Digitization in business refers to the act of adopting digital technologies within the routine operations of firms. Under the general background of elevating market survival pressure and depletion of market capacity, digitization became a standard solution for firms to improve corporate productivity. This research collects data on digital technology adoption and corporate financial metrics to explore the relationship between country-level digitization, firm-level productivity, and the formation of imperfectly competitive market structures. By employing the fixed effects-ordinary least squares (FE-OLS) regression analysis, we found that adopting certain national technologies can lead to improved productivity on the firm level. In addition, while connectivity-enhancing digitization encourages the formation of centralized market structures, internal-managing digitization tends to benefit small firms more and lead to more decentralized markets. The robustness of outcomes is also retested using various techniques.

1. Introduction

Over the course of the 21st century, even with the increased emphasis on productivity, the contraction of resource availability and market potential has become a problem in the modern business landscape. Against such a background, society experiences a shift in production strategy from the Fordist mode of relying on expanding economies of scale and enlarging production input to the new lean method, where firms emphasize capital's employment efficiency and the operations' output-input ratio.

The advantages of the lean mode are self-explanatory. Firms now face a more comprehensive array of issues, such as profit loss due to increased competition, environmental concerns, and global economic uncertainties. Corporations must use their resources productively to overcome these challenges and avoid waste generation. They must also discover new ways to attract consumers with existing resources, which creates new markets.

Consequently, the demand for firms to increase efficiency has led to the development of information technology and digital industries. As a crucial component of the newly emerged digital economy concept, digital servitization and the employment of digital capital have allowed firms to strengthen their productivity powerfully. Overall, digital adoption may increase firms' productivity by increasing the efficiency of

information exchange and promoting transparency in economic activities. The invention of the broadband internet in 1996 first created the general platform of virtual information exchange and storage. In recent years, the development of cloud computing, robotic process automation, resource management planning, and AI-assisted tools have all played essential roles in promoting efficiency in different industries. However, how these technologies are used may vary across industries due to differences in capital structure and means of production.

Apart from the industry-level differences, the differences in digital technology adoption also occur on the national level. Digital adoption rates may differ in different countries depending on developing economic status or technological advancements. Country-level digital adoption can also reshape the market structure of particular industries, as some firms may benefit more from digitization than others.

This investigation mainly focuses on how country-level digital technology adoption rates correlate with firm-level productivity and changes in market structure. We will combine the use of qualitative literature reviews and quantitative empirical analysis as our research method. Specifically, we will employ the fixed-effects ordinary least squares (FE-OLS) regression analysis to process the data collected. Our results suggest a positive correlation between firm productivity and country-level digitization rates for specific technologies.

This research has a noteworthy level of importance. As explained, the issue of increasing market competition and elevated levels of commercial stress may stagnate many developing countries in the long run. By identifying the relationship between certain technologies and analyzing how they boost economic efficiency, firms can be provided with a more precise direction regarding which technology to invest more in and whether they are in the best region for enhanced digital adoption. Policymakers can also learn the relationship between digital technology and market structure changes.

This paper is organized as follows: Section 2 will provide a literature review; Section 3 will present the hypotheses and modeling details; Section 4 will show the descriptive statistics and address the empirical findings; Section 5 will check the robustness of the study; and Section 6 will offer a discussion of the results.

2. Literature Review

2.1 Overview of Digitization Trend

To begin with, we can gain a global perspective by looking at several conceptual studies that discuss the overall trend of digitization. These studies usually reach their conclusions using qualitative measures. For example, Goldfarb and Tucker, 2019, have broadly mapped the digital economics sector. Their paper explains how digitization decreases friction in economic activities and, for the manufacturing sector, can lower the costs of transporting, verifying, and tracking information due to the replicable and immediate nature of information access and the growth in cybersecurity.

Although some studies approve of the association between productivity and digitization, other papers hold mixed opinions. For example, Brynjolfsson addressed the famous Turing Trap theory in his 2022 paper. AI-related digital adoptions can be classified into two subtypes: human-like artificial intelligence (HLAI) or human-augmenting artificial intelligence (HAAI). While HLAIs and HAAIs can both enhance productivity, the Turing Trap warns that the excessive deployment of HLAIs may result in decreased productivity on an aggregate level due to increased structural unemployment, loss in bargaining power for the replaced human labor, and increased inequality in wealth distribution as more resources concentrate to entities who are in control of the technology, which might distort the competitiveness of markets.

2.2 Complexities in Associations

While most conceptual papers recognize the overall efficiency improvement of digitization, evidence from empirical research suggests a more complicated correlation between digital adoption and firm productivity. Some articles do uncover an implicit correlation with the conceptual studies. For example, Basaez et al. 2018 concluded that including digital servitization in the automotive industry produces significant firm-level gains in customer satisfaction and overall productivity Other researchers, such as Syverson 2011 and Akerman et al. 2013, have argued that the employment of digital technologies enables an increase in the flow of information, which leads to greater efficiency in the research & development (R&D) sectors, in turn leading to higher productivity.

However, there is also literature that discovers anomalies. A 2022 literature study by Nyoni, Ndayizigamiye, and Bvuma mentioned that in developing countries, while individual firms may benefit from digital adoption, such effects will be offset on a broader level as the more-digitized firms suppress the growth potential of less-digitized firms, driving them out of business and forming industry-level inequalities. As the beneficiary firms obtain higher profit margins, domestic consumers might suffer from price rises for goods and services. An example of this effect occurs in the software development industry in African countries (e.g. Nigeria, Democratic Republic of the Congo, etc.).

Similarly, a 2022 report drafted by the International Monetary Fund (IMF) has found that during the COVID-19 pandemic, the crowding-out effect of digital technologies on employment was more significant due to an overall decline in business confidence and a decreased general willingness for firms to hire labor. The quarantine policy implemented in multiple countries also increased the reliance of the production sector on digital technologies and lifted the substitution effect of digital capital over human resources. However, in this respect, we may discover the issue of confounding correlations. During the COVID-19 pandemic, it was hard to determine whether the increased unemployment was caused by the over-adoption of digital technologies or the quarantine policy.

One way to explain the heterogeneities of conclusions is the reality that digital tools by themselves have very ambiguous effects on economic activities. Their positive results are usually the effect of amplifying other corporate advantages such as worker skills, market loyalty, and the managerial quality of firms. For example, with data evidence, Gal et al. 2019 have illustrated that more productive firms benefit more from digital adoption. The research implies that firms that obtain a considerable boost from digitization usually have an above-average skill level, market presence, and decision-making literacy. Therefore, adopting digital technologies can potentially encourage industry-level Matthew effects as the stronger firms become more robust, further weakening firms that are already weak.

2.3 Regional Differences

A new evaluation aspect is considering regional technological usage differences. Chinn and Fairlie 2004 surveyed respondents from 161 countries and found that internet users and firm representatives from different countries have very different attitudes toward internet adoption. While users from MEDCs, such as Canada and the United States, are more welcoming of personal computers, those from the LEDCs, such as Thailand and Cambodia, are more reserved towards internet usage. LEDC firms also rely more on offline marketing rather than digital strategies. However, Wagh and Shaikh 2021, Peters 2016, and Khan et al. 2021 all discovered that digitization in the manufacturing sector leads to enhanced production outputs and a more convincing input-output ratio in developing economies. One common argument is that developing countries tend to have a less competitive economy and larger labor supply. Therefore, by arranging these resources more efficiently, firms in developing countries gain more through digital usage.

2.4 Literature Conclusion

We can streamline all the information in this chapter into several summary conclusions. First, most studies have recognized the role of digital technologies in enhancing production efficiency in the general case. Second, the effect of digital adoption on productivity varies depending on economic stability and how the technologies complement other existing firm-level capital. When analyzing these effects, confounding factors should not be neglected. Third, a common byproduct of digitization is the formation of industry-level inequalities and declining market competition. Fourth, there are observable regional differences in digital technology usage and significant spillover effects of one firm's digital adoption on other firms' performances.

3. Methodologies and Modeling

3.1 Hypotheses and Explanation

3.1.1 Digitization and Productivity

Regarding the relationship between digitization and productivity, we propose **H1:** *Country-level adoptions of specific digital technologies correlate positively with firm-level productivity.*

Prevalent economic theories can give us a general idea of how goods and services are produced and how digitization joins the production process. We can interpret the effects of digital technology adoption using a Cobb-Douglas production function model, assuming diminishing marginal returns:

$$Y = F(K, L) = AK^{\alpha}L^{1-\alpha}; \ (0 < \alpha < 1) \tag{1}$$

In equation 1, the production of goods and services is realized by capital and labor input (Cobb and Douglas 1928). Y indicates actual output, and A represents total factor productivity. K and L represent capital and labor input, respectively. α takes a value between 0 and 1 to account for the effect of marginal diminishing returns. In this function, digital adoption can enter as a part of A or K. In this research, we assume it enters in the component of A, as several studies argue how digitization increases firm output by operating in tandem with physical capital (Gal et al. 2019; Basaez et al. 2018; Syverson 2011) rather than serving as a part of physical capital. Thus, the effect of an increase in digital adoption can be seen in Figure 1:
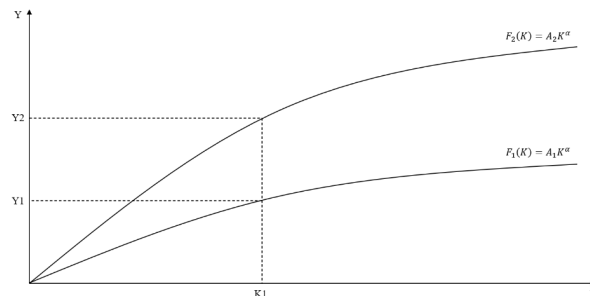
Figure 1. *Effect of Digitization*

As shown above, an increase in digitization can increase the total factor productivity, A, which shifts the production function from $F_1(K)$ to $F_2(K)$. Since A is the function's leading coefficient, an increase in A means that at every quantity of capital K, the actual output is increased by a fixed ratio, which implies a potential positive linear relationship between

digital adoption and A. For example, with a fixed capital stock K_1, a typical firm increases its output from Y_1 to Y_2 when digitized, signaling increased productivity.

3.1.2 Digitization and Market Structure

Regarding the relationship between digitization and market structure, we propose **H2:** *Country-level adoptions of specific digital technologies can be associated with higher market power and an imperfectly competitive market structure*.

Apart from the productivity argument, another field of interest of this research is how digital adoption distorts the market structure of industries. In section 2, we analyzed several studies that discover how digitization benefits larger firms more and will therefore stagnate the relative competitiveness of smaller firms (Nyoni et al. 2022; Gal et al. 2019). This point seems understandable in the production function. If firms initially obtain a high value of K, and thus economies of scale, multiplying it with an identical increase in A naturally brings a more significant boost in actual output than firms with a small stock of K. However, this explanation does not account for the effect of increasing price levels and firm profits found by the researchers.

To explain this change, we will use the model of imperfect competition developed by Joan Robinson. Unlike a perfect competition scenario, an imperfectly competitive market arises when firms gain market power (Robinson 1933). The source of market power is known as economic moats. Digital adoption enters this model as an economic moat, where larger firms withhold advanced digital tools to construct market barriers against smaller firms and become "price makers" instead of "price takers" in a perfect competition market. This effect is illustrated below in Figure 2:
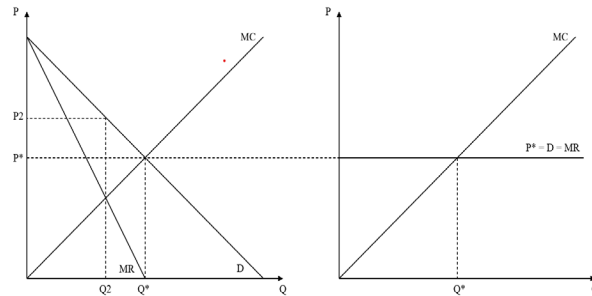
Figure 2. *Imperfect Competition*

As illustrated, when firms gain more market power from digitization, they face a downward-sloping demand curve rather than the horizontal demand curve in the perfect-competition scenario. Assuming all firms maximize their profits ($MC = MR$), an imperfectly competitive market has a higher average profit margin than a perfectly competitive market. ($P_2 > P^*$) Conversely, keeping the industry and the type of commodity constant, a market with high equilibrium prices can also signal higher profits and imperfect competition.

3.2 Variables

Based on the above theoretical framework, we introduce the variables below as our variables of interest in this research:

Table 1. *Variable Description*

Variable	Type	Description
REV		Total revenue of firms, in 2015 U.S. Dollar
EMP	Dependent	Number of employees firms officially employed
PM		Profit margin of firms
ROCE		Return on capital employed
BB		% of firms with access to broadband
CC		% of firms with cloud computing
CRM	Independent	% of firms with digital consumer relations management
CW		% of firms with a commercial website
ECS		% of firms that have E-Commerce Sales
ERP		% of firms that have enterprise resource planning
NAT	Controlled	The nation that firms operate in
IND		The industry that firms operate in

Following Basaez 2018, we introduce a new variable, average labor productivity (APL), as the revenue generated per each employed worker, to quantify the productivity of firms:

$$APL = \frac{REV}{EMP} \tag{2}$$

The country-level digitization data are taken from the Eurostat Innovation and Digitization database, covering 34 countries in the Eurozone over 2015-2019. We classify the six technologies into connectivity-enhancing technologies (BB, CW, ECS) that strengthen firms' information exchange efficiency with other firms, and internal-managing technologies (CC, CRM, ERP) that improve firms' efficiency of internal resource arrangements. The firm-level data is retrieved from the ORBIS financial database.

We modify both datasets by omitting firms with fewer than 10 employees, to ensure that the selected firms have a certain level of operational consistency. Also, since we are interested in per-capita figures, a small number of employees may increase the volatility and error of the APL variable. We also restrict our research scope to firms with more than 10 patents because we want firms to have baseline intellectual property stock to ensure that they have the ability and are willing to use digital tools as routine assistance.

3.3 Model Specification

3.3.1 Digitization and Productivity
In this research, we will use the linear fixed-effects model below to analyze the relationship between digital adoption and productivity:

$$APL_{ijct} = \alpha_0 + \alpha_1 BB_{ct} + \alpha_2 CC_{ct} + \alpha_3 CRM_{ct} + \alpha_4 CW_{ct} \tag{3}$$
$$+ \alpha_5 ECS_{ct} + \alpha_6 ERP_{ct} + \delta_j + \gamma_c + \mu_t + \varepsilon_{ijct}$$

Here, α_0 represents the constant term, ε_{ijct} contains the random error of the linear model, and α_1 - α_6 indicates the coefficients of interest, which governs the baseline linear relationship between digital technology adoption and productivity. Mathematically, they determine by what percentage the firms' productivity will change if the nation it operates in experiences a 1% increase in technology adoption. In other words, they indicate the elasticity of firm-level productivity to country-level digital adoption. If **H1** holds, we expect at least one of the α_1-α_6 coefficients to be positive.

One unique characteristic of this regression framework is the differences in observation levels. While the dependent variable is on the firm level, the independent

variables are on the country level. Constraint of data availability is one reason. But more importantly, following Gal et al. 2019 and Nyoni et al. 2022, setting independent variables on a broader observation level can better account for the spillover effect of firms on other firms in the same nation. This feature will be useful when we interpret the second regression model concerning the relationship between digitization and market structure distortions.

However, statistical noise is a downside of using a model like this. Since the independent variable occurs on a higher observation level than the dependent variable, a considerable number of firm-level variations cannot be explained by the country-level data. To overcome this problem, we incorporate fixed effects to control for confounding factors that may create unexplained variations. δ_j, γ_c, and μ_t are 3 fixed-effect vectors that contain industry, country, and year differences, respectively. We can limit the statistical noise to a satisfactory level by controlling for these differences. Also, to avoid statistical noise caused by outliers, we use the robust standard error when running the regression.

3.3.2 Digitization and Market Structure

To test our second hypothesis, we will use the similar linear fixed-effects model introduced in the last subsection with a different dependent variable:

$$PM_{ijct} = \beta_0 + \beta_1 BB_{ct} + \beta_2 CC_{ct} + \beta_3 CRM_{ct} + \beta_4 CW_{ct} \qquad (4)$$
$$+ \beta_5 ECS_{ct} + \beta_6 ERP_{ct} + \delta_j + \gamma_c + \mu_t + \epsilon_{ijct}$$

Here, changes in market structures are represented by variable PM, which is the firms' profit margins. We used Robinson's theory of imperfect competition to illustrate how higher market prices and abnormal profits for firms characterize a more monopolized market structure. The industry and country-fixed effects can control most other confounding factors, such as industry differences (e.g., luxury retail having a higher profit margin than grocery retail) and national features (e.g., oil refining in the Middle East regions). If **H2** holds, we expect at least one of the β_1-β_6 coefficients to be positive.

4. Empirical Findings

4.1 Descriptive Statistics

Table 2. *Descriptive Statistics*

Variable	μ	Min	25th	50th	75th	Max	σ	N
APL	$1.07E^3$	$-1.04E^5$	170	274	462	$4.89E^6$	$2.09E^4$	$1.30E^5$
ROCE	11.6	-976	3.36	9.71	18.7	974	32.1	$1.24E^5$
PM	5.54	-99.4	1.05	4.62	9.99	99.8	12.9	$1.24E^5$
BB	96.5	66.0	95.8	96.7	97.8	100	2.81	170
CC	37.3	4.30	20.3	30.8	58.1	85.2	20.6	170
CRM	34.6	4.30	30.0	32.2	42.8	55.8	7.95	170
CW	12.9	2.90	9.10	11.6	15.5	26.5	4.35	170
ECS	21.3	1.30	15.7	23.5	26.4	46.8	7.83	170
ERP	33.3	8.20	27.2	35.4	38.1	56.5	10.7	170

In addition to the descriptive table, we can also investigate the technology adoption of countries in the following boxplot:
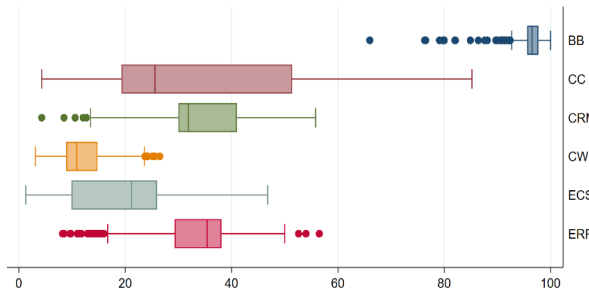
Figure 3. *Technology Adoptions Boxplot*

As seen above, most selected technologies have a mean national adoption rate between 20% and 40%. Since broadband technology is relatively mature, many countries have approached a 100% adoption level. However, several nations are lagging behind on this metric, with the smallest observation close to 60%.

On the other hand, the commercial website has the lowest adoption rate among all six technologies, which is understandable since e-commerce is a relatively newly emerging business model. Also, one social factor is that consumers in many countries are still more accustomed to the traditional brick-and-mortar shopping experience and have not yet transferred to the virtual purchasing mode of retailing (Chinn and Fairie 2004). This lag on the demand side can discourage firms from adopting commercial websites and enable them to continue with what is currently working.

Regarding data dispersion, we see cloud computing with the broadest distribution of observation, likely caused by the control of patents (Daniele 2023). Most technologies and patents related to cloud computing originate from Northern European countries (e.g., Sweden, Finland, and Denmark). As these nations control the majority of patents, they obtain the high ground (larger than 80% on the plot) in cloud computing adoption. Other countries, such as Hungary, Greece, and Romania, do not have control of cloud computing, which limits them to a relatively low position on the boxplot.

4.2 Modeling Outcomes

4.2.1 Numerical Results
The baseline regression results of the two models are presented in Table 3[1]:

Table 3. *Baseline Regression Results*

	(1) APL	(2) ROCE	(3) PM
BB	82.1***	0.240***	0.0655***
	(15.4)	(0.069)	(0.030)
CC	5.65**	0.0352**	-0.0118**
	(2.76)	(0.014)	(0.006)
CRM	13.4	0.0207	0.0205
	(9.69)	(0.050)	(0.020)
CW	58.4***	0.212***	0.0125
	(19.20)	(0.097)	(0.036)
ECS	-25.7	0.00165	0.101***
	(14.21)	(0.053)	(0.019)
ERP	9.44	0.0459**	-0.0266***

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[1] This chart shows the linear regression results. The brackets present the robust standard error of each variable. *, **, and *** represents significance at level 10%, 5%, and 1% respectively.

	(1) APL	(2) ROCE	(3) PM
Constant	(6.89) -6.99E^3*** (1.24E^3)	(0.023) -20.1*** (7.45)	(0.008) -7.78 (6.33)
Nation FE	YES	YES	YES
Industry FE	YES	YES	YES
Year FE	YES	YES	YES
Adjusted R^2	0.0071	0.0285	0.0423
N	130,193	124,115	124,115

4.2.2 Interpretation on Productivity

The regression chart shows that most investigated technology adoption has a positive coefficient (BB, CC, CRM, and CW), which provides us with baseline insurance of the correctness of **H1**. The country-level adoption of broadband networks, cloud computing, commercial websites, and e-commerce revenue stream statistically correlates with firm-level productivity. We interpret the coefficients according to the distribution of the variables. For example, for cloud computing, we take the interquartile range of the variable ($58.1 - 20.3 = 37.8$). Then, we multiply it with the regression coefficient ($37.8 \times 5.65 = 213.67$) and add it to the median of APL ($213.57 + 273.58 = 487.15$). We next divide the value by the standard deviation of CC ($487.15 \div 2.09E^4 = 0.023$); this shows that for 1 unit of increase in country-level adoption of CC, there is a 0.023 s.d. increase in firm-level average labor productivity.

This research also uses the return on capital employed (ROCE) as the second metric to measure firm-level productivity from another angle. ROCE measures the efficiency of a firm's employment of capital. Although it is a similar variable to APL, it emphasizes the employment efficiency of capital instead of labor. Still, it is a valid variable to be used here as an alternative estimator of firm productivity. Model (2) provides nearly identical outcomes as model (1); the only difference is a gain in the significance of enterprise resource planning. Since ROCE emphasizes capital efficiency, it is logical to interpret that it values ERP (which essentially manages a firm's capital resources) more.

One challenge in interpreting these results is explaining the relationship across different observation levels. How does national-level technological adoption influence firm-level productivity? Are all domestic firms affected uniformly?

One plausible idea is technology diffusion from national to firm levels. Raj and Seamans 2019 have pointed out the deficiency of disaggregated firm-level data and articulated how AI technologies generally diffuse among firms. When many firms adopt artificial intelligence technology, they lift the country's general adoption rate of AIs. Such effects will diffuse into other firms in two forms: first, other firms in the same industry will begin to adopt similar technology if possible; second, if firms are unable to acquire the technology, they will try to increase productive efficiency by cutting off less important operations or by unemploying excess labor. In both scenarios, the increase in firm productivity is driven by market competition. Juhasz et al. 2020 provided a similar explanation concerning the cotton industry, where productivity rise was caused by technology adoption on a higher level, as it triggers the need for individual firms (especially newcomers) to reorganize their production under the new technology. However, both authors addressed that market competition can oppose firm-level productivity, as digitized firms may gain more advantages than undigitized firms in resource acquisition.

Alternatively, another interpretation of cross-level influence can be linked to the theory of network externalities, where the benefit for each user in a network increases when it grows. With empirical evidence, Zhang et al. 2020 have argued that resource creation or innovation efforts on a network level (outside of individual firms) may benefit

all firms in the network. Innovation efforts on an aggregate level can increase overall macroeconomic confidence, encouraging individual firms to increase their investments in research & development. More importantly, digitization that facilitates the connection between firms, such as wireless technologies and telecommunications, has more significant positive network externalities. As the country experiences increases in overall internet connectivity, more ideas and knowledge can be exchanged, and therefore generated, with no discernible increase in the labor force, ultimately increasing productivity on a firm level.

Linking back to our results, our study classifies the six technologies into internal-managing technologies (CC, CRM, and ERP) and connectivity-enhancing technologies (BB, CW, and ECS). The interpretation provided by Raj, Seamans, and Juhasz et al. addresses why, generally, adopting digital technologies on a broad level can promote each firm to increase efficiency by elevating competitive market pressure. On the other hand, The interpretation provided by Zhang et al. 2020 specifically explains how communication-enhancing technologies such as broadband and commercial websites significantly affect productivity through network externalities.

4.2.3 Interpretation on Market Structure

Like the productivity model, the market structure model also yielded reasonable outcomes, where country-level broadband connectivity and e-commerce sales have statistically significant positive correlations with firm-level profit margins. For example, a 1 unit increase in country-level adoption of ECS will lead to a 0.442 s.d. increase in firm-level profit margin, which validates **H2**.

As noted previously, adopting technologies, in general, can elevate market competition for each firm in a specific country or industry. Although the desired outcome is that firms detect the upcoming threat and make in-time adjustments, the more realistic result is that due to operational rigidities and the overall lack of reaction time, small firms that have smaller supply elasticities and a smaller range of selectable scales of production cannot make adjustments as quickly and effectively as larger firms. Defeo 1986 has concluded, backed by empirical data collection, that when the market response is defined as a change in the variance of firm returns distribution, smaller firms were associated with significantly longer intervals of adjustment time.

One commonality between the two positively significant technologies is that they are both connectivity-enhancing. If we follow the logic in the last section, adopting this kind of technology on a country level should benefit all firms operating in that country due to network spillovers. However, the magnitude of such a benefit is often proven to be disuniform for firms that enter the network at different times. An early-entering firm should have advantages over later-entering firms, as they have preliminary access to the novel consumer basis. They also have more time to structure their strategy compared to other firms. Ahi and Sinkovics 2023 analyzed how the benefits provided by e-commerce are distributed among different firms. They concluded that firms that enter the network the earliest will have a start-up advantage against the latecomers. Also, they have evidence showing that small and medium-sized businesses (SMEs) lag behind larger firms in adopting e-commerce, which explains how these connectivity-enhancing technologies can increase the profit margins of larger firms and create more centralized market structures.

However, unlike the productivity model, which offers an overall consistent result among technologies, the profit margin model involves two technologies with significantly negative coefficients: cloud computing and enterprise resource planning, both internal-managing technologies. It implies that country-level adoption of cloud computing and enterprise resource planning decreases firm-level profit margins and discourages imperfect markets. Bloom and Pierri 2018 have pointed out that cloud-based technologies, such as cloud computing and enterprise resource planning in our case, have strengthened SMEs more than larger businesses. The research suggests that transferring data processing and day-to-day operations into the cloud can exempt small firms'

requirements to acquire their own computer and physical technology stock, significantly reducing overhead costs. In the case of larger firms, this cost-saving effect is relatively less notable. As a result, cloud-based digitization provides a catch-up boost for small firms, which therefore maintains the decentralized market structure in specific industries or countries and avoids the frequent occurrence of highly-profitable large firms.

4.3 Baseline Conclusion

We currently find that country-level adoptions of certain technologies promote firm-level productivity via market competition and network spillovers. Also, while connectivity-enhancing technologies consolidate imperfect markets, internal-managing technologies benefit smaller firms more and, to an extent, suppress the formation of monopolies.

5. Robustness Checks

5.1 Variance Inflation Factor (VIF) Multicollinearity Test

One risk of linear regression is multicollinearity, the linear correlation among independent variables. We run a Variance Inflation Factor (VIF) test to check for multicollinearity.

Table 4. *VIF Multicollinearity Test*

Variables	VIF
BB	1.41
CC	1.59
CRM	2.10
CW	2.29
ECS	2.34
ERP	1.64

As shown above, all variables have VIF < 5, signaling weak multicollinearity. However, a limitation of VIF is that it cannot check for high-order multicollinearity when more than 2 variables correlate simultaneously with one another.

5.2 Using a Subset of the Original Dataset

To check the robustness of the models, we will run the same regression using subsets of the original dataset. The results are shown in Table 5[2]

As seen in Table 5, the ROCE model and the profit margin model are used in this robustness check. Here, we use a subset with a size $\frac{1}{5}$ of the original dataset. Although nearly all variables experience a decline in correlation significance and an increase in robust standard errors, such an effect is expected due to a dramatically shrunken sample size. Overall, the implication of the results stayed essentially the same, with the variables performing similarly compared to the complete set, strengthening our regression analyses' robustness.

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[2] This chart shows the linear regression results. The brackets present the robust standard error of each variable. *, **, and *** represents significance at level 10%, 5%, and 1% respectively.

Table 5. *Subset Regressions*

	(2) ROCE (Full-Set)	(4) ROCE (Subset)	(3) PM (Full-Set)	(5) PM (Subset)
BB	0.240***	0.311**	0.0655***	0.0801*
	(0.069)	(0.145)	(0.030)	(0.0638)
CC	0.0352**	0.0152**	-0.0118**	-0.0467**
	(0.014)	(0.0133)	(0.006)	(0.004)
CRM	0.0207	-0.094	0.0205	-0.188
	(0.050)	(1.023)	(0.020)	(0.363)
CW	0.212***	1.782***	0.0125	0.142**
	(0.097)	(0.671)	(0.036)	(0.059)
ECS	0.00165	0.0306	0.101***	0.604**
	(0.053)	(0.619)	(0.019)	(0.344)
ERP	0.0459**	0.0371***	-0.0266***	-0.151*
	(0.023)	(0.0104)	(0.008)	(0.055)
Constant	-20.1***	-36.3	-7.78	8.57
	(7.45)	(97.2)	(6.33)	(56.9)
Nation FE	YES	YES	YES	YES
Industry FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Adjusted R^2	0.0285	0.0739	0.0423	0.0598
N	124,115	24,823	124,115	24,823

6. Conclusion

In conclusion, our research investigates the relationship between country-level adoption of digital technologies and firm-level productivity, as well as the formation of imperfect competition market structures. Overall, we draw the following implications:

First, we classify the six selected technologies into connectivity-enhancing and internal-managing technologies. Regarding the relationship between country-level digitization and firm-level productivity, we find that adopting certain technologies on a broad level does associate positively and significantly with the productivity of individual firms. Such effect transfers across observation levels through the imposition of market pressure from more digitized firms to less digitized ones and through the network effects, augmented especially by connectivity-enhancing technologies. This conclusion aligns with our hypothesis **H1**.

Second, regarding the formation of market structures, we find that different sorts of digitization influence different firms at different magnitudes. Connectivity-enhancing technologies tend to favor larger firms more than SMEs, giving larger firms early access to new consumer interfaces. Therefore, adopting them can encourage the occurrence of highly profitable firms and centralized markets, which aligns with our hypothesis **H2**. On the other hand, internal-managing technologies tend to favor SMEs more than larger firms, as their cost-saving function is more highly valued by SMEs than by larger firms. Therefore, adopting them can grant SMEs a catch-up boost, thus maintaining the competitiveness of markets and promoting a decentralized market structure.

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The Relative Persuasiveness of Gain- and Loss-Framed Messages on Changing Drivers' Attitudes Toward and Intentions to Perform Aggressive Driving Behaviors

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Abstract

This study investigated the relative persuasiveness of gain-framed and loss-framed messages on changing drivers' attitudes toward aggressive driving and intentions to drive aggressively. To simulate a frustrating driving situation in real life, a pilot study was carried out to test a scripted scenario on believability and efficacy in inducing frustration among drivers. This scenario was deemed believable and effective in inducing frustration, and based on the feedback, changes were made to further improve its realism and efficacy. Then, the main study used a pretest-posttest approach to determine which message out of five (one unframed + two gain-framed + two loss-framed) had a persuasive advantage on (a) changing drivers' attitudes toward aggressive driving, (b) changing their intentions to drive aggressively, and (c) helping the advertisement receive the most positive evaluation from the audience. As a result, the messages did not have a statistically significant effect on either attitude change or the specific evaluation measures of the advertisement. However, the messages had a statistically significant effect on changing drivers' aggressive driving intentions. Post hoc analyses revealed a gain-framed message describing the removal of an undesirable kernel state (theme: fatal crash; people involved: driver, passenger, other road users; medium: video ad) to be the most effective message in reducing drivers' intentions to perform aggressive driving behaviors. The implications and limitations of the findings were discussed, and suggestions for future research were proposed.

1. Introduction

For many people, a road trip would be a fun and relaxing activity, yet it would not be if they were confronted by aggressive drivers. In reality, the problem of aggressive driving goes beyond ruining people's good mood. It is a threat to the safety of road users around the world. In fact, this problem is closely related to target 3.6 of the United Nations Global Goals: "reduce road injuries and deaths" (United Nations, n.d.). Therefore, it is increasingly urgent for the scholarly community to delve into this problem and discover the possible ways to effectively tackle it.

Approaching this issue with persuasive marketing techniques, this research aims

to discover which persuasive message out of all gain- and loss-framed messages is the most persuasive in changing drivers' attitudes and intentions to drive aggressively, hence contributing to the resolution of this global issue. To start, this section introduces three foundational concepts: aggressive driving, the gain- and loss-framed appeals, and the persuasive effects measured in this study.

1.1. The Problem: Aggressive Driving

In social psychology, aggression is defined as an act performed with the intent to harm an individual who "does not want to be harmed" (Allen & Anderson, 2017; Bushman & Huesmann, 2010, p. 833). As a type of aggression, aggressive driving should be defined with regard to this definition. Therefore, in this study, aggressive driving is defined as the behaviors that are performed by the driver with the intent to harm other road users "physical[ly] and/or psychological[ly]" while being in their car (Dula & Geller, 2003, p. 565). These behaviors include "tailgating," obscene "gesturing," "running red lights," etc. (for the full list, see Tasca, 2000, p. 10).

To ensure accurate discussions, it is necessary to distinguish aggressive driving from other confounding concepts, namely risky driving and road rage. Compared to aggressive driving, risky driving also encompasses behaviors that do not necessarily affect others but are hazardous for the drivers themselves, such as not "wearing a seat belt" when driving (Tasca, 2000, p. 14). The difference between aggressive driving and road rage greatly resembles that between aggression and violence, in that the latter concept is respectively a more severe and extreme version of the former one (Allen & Anderson, 2017; Tasca, 2000). For this reason, road rage is often perceived as a "rare" criminal act, while aggressive driving is considered a "traffic offense" that occurs more frequently in life (AAA Foundation for Traffic Safety, 2009; National Highway Traffic Safety Administration, 1999; Tasca, 2000, pp. 4, 9). In addition, one must keep in mind that because aggressive driving is carried out with the deliberate intent to cause harm, the dangerous driving behaviors stemming from accidents and/or mental inattention are not considered aggressive driving, hence not considered in this research (Bushman & Huesmann, 2010; Tasca, 2000).

Past studies in the traffic safety literature have revealed aggressive driving as an effective predictor for traffic accidents (Čabarkapa et al., 2018; Chliaoutakis et al., 2002). From 2003 to 2007, aggressive driving behaviors were spotted in 55.7% of the lethal traffic crashes in the U.S. (AAA Foundation for Traffic Safety, 2009). This problem was commonly found in crashes between two or more vehicles (AAA Foundation for Traffic Safety, 2009). Furthermore, aggressive driving behaviors occur frequently among drivers. In 2014, 78.1% of U.S. drivers reported that they had driven aggressively "at least once" in the preceding year (AAA Foundation for Traffic Safety, 2016). In addition, past studies have discovered that aggressive driving could trigger a ripple effect of aggression on the road. The aggression of one driver could irritate other drivers, and simply observing an "unpunished" aggressive driver could also undermine other drivers' abilities to refrain from driving aggressively (AAA Foundation for Traffic Safety, 2009; Björklund, 2008; Novaco, 1998, p. 5). Over the years, this problem barely improved. For instance, in 2021, the aggressive driving behavior of speeding proliferated in multiple U.S. states (Sharp). Outside the U.S., many sources have spotted the presence of this issue in China (e.g., Wang et al, 2010), Thailand, Australia, Indonesia (e.g., Piyakul & Chomeya, 2012), Israel (e.g., Shinar, 1998), and many other countries, hence revealing the global significance of this issue.

The nature of aggressive driving is complex, as it is attributable to both personal and environmental factors. For instance, past studies have found demographical and dispositional factors like young age, endorsement for macho personality (Krahé & Fenske, 2002), narcissistic personality (Bushman et al., 2018), and "Type A behavioral pattern" (Miles & Johnson, 2003, p. 154) to be effective predictors of a driver's propensity to drive

aggressively. The environmental factors that correlate with aggressive driving behaviors or intentions include possessing and maneuvering "high-performance cars" (Krahé & Fenske, 2002, p. 27), the identity of the passenger(s) in the car (Hu et al., 2012), the duration of the green traffic light (Shinar, 1998), and whether the driver is the "initiator" or the "retaliator" of an aggressive driving event (Parker et al., 1998, pp. 14-15). Furthermore, past studies discovered that drivers with greater intent to drive aggressively tended to find controlling their aggressive driving behaviors challenging (Parker et al., 1998) and that aggressive drivers often have poor awareness of their aggressive driving styles (Miles & Johnson, 2003). Therefore, it is deemed that certain external regulations or designs may be necessary to help drivers avoid driving aggressively, such as the gain- and loss-framed appeals examined in this study.

1.2. Gain- and Loss-Framed Appeals

According to Teng et al. (2019), influential organizations, such as the World Health Organization and the U.S. Department of Transportation, are supportive of using media campaigns to address concerns about traffic safety. The reachability of media is particularly in favor of tackling aggressive driving, in that this problem concerns a large population.

The core of a media campaign is its message. In the persuasive marketing literature, researchers have investigated how to frame a message in a way that accentuates behavior change. One such technique is to describe the gains of "compliance" or the losses of "noncompliance," which are respectively called a "gain-framed appeal" and a "loss-framed appeal" (O'Keefe & Jensen, 2007, p. 623).

Both appeals originated from the Prospect Theory, which challenged the concept of rationality with the idea that a decision-maker would avoid risks when the consequence is presented as a gain but pursue risks when it is presented as a loss (Tversky & Kahneman, 1981). Although this theory was proposed based on the context of decision-making but not behavior change, marketing practitioners have transferred this concept to the persuasive marketing field by investigating whether presenting the consequence(s) of an action as gains or losses would accentuate the message's persuasive power on behavior change and adoption.

According to O'Keefe & Jensen's (2007) 2 x 2 array, there are two forms of gain-framed appeals and two forms of loss-framed appeals. These four variations, presented in Figure 1, are the result of manipulating two variables: (a) whether the kernel state (henceforth KS)—i.e., the statement that describes the consequence(s) of an action—in a message is desirable or undesirable in nature and (b) whether that KS is described as being obtained or removed due to complying or refusing to adopt the behavior suggested by the message (O'Keefe & Jensen, 2007).

Figure 1. *The Four Variations of Gain- and Loss-Framed Appeals (Rothman & Salovey, 1997, p. 6)*

Therefore, a gain-framed appeal can choose to describe either the obtainment of a desirable KS (Cell A) or the removal of an undesirable KS (Cell D), and a loss-framed appeal can choose to describe either the removal of a desirable KS (Cell C) or the obtainment of an undesirable KS (Cell B).

One comprehensive example of applying this 2 x 2 array is Apanovitch et al.'s (2003) research, which promoted HIV screening with a desirable KS of having "peace of mind" and an undesirable KS of experiencing anxiety (p. 62). With these two KS, Apanovitch et al. (2003) developed two gain-framed messages: "...If you decide to get HIV tested[,] you may feel the peace of mind that comes with knowing your health..." (Cell A, obtaining a desirable KS due to compliance) and "...If you decide to get HIV tested, you may feel less anxious because you won't wonder if you're ill..." (Cell D, removing an undesirable KS due to compliance; p. 62). They also penned two loss-framed messages: "...If you decide not to get HIV tested[,] you won't feel the peace of mind..." (Cell C, removing a desirable KS due to noncompliance) or "...If you decide not to get HIV tested, you may feel more anxious..." (Cell B, obtaining an undesirable KS due to noncompliance; Apanovitch et al., 2003, p. 62).

Likewise, this study would apply the entire 2 x 2 array when framing messages regarding gains or losses. In addition, to ensure accurate discussions in subsequent sections, this study would distinguish "gain- and loss-framed *appeals*" from "gain- and loss-framed *messages*." The word "appeal" refers to the technique of framing messages regarding the gains of "compliance" or the losses of "noncompliance" (O'Keefe & Jensen, 2007, p. 623), whereas the term "message" specifically refers to the message produced by applying this technique.

1.3 Persuasive Effects: Change in Attitude and Behavioral Intention

To measure the efficacy of persuasive messages in tackling the issue of aggressive driving, this study would measure two persuasive effects: attitude change and intention change. To understand the relationship between these variables with actual behavior change, it is necessary to introduce Icek Ajzen's (1991) The Theory of Planned Behavior, presented in Figure 2.
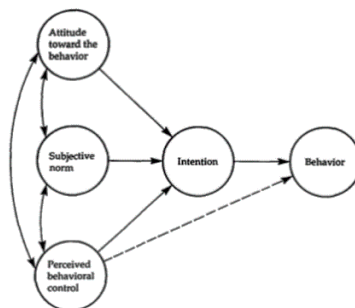
Figure 2. *The Theory of Planned Behavior (Ajzen, 1991, p. 182)*

In this model, Ajzen (1991; 2011) proposed that behavioral intention, defined as one's willingness to perform a behavior with autonomy, is a direct predictor for actual behavior, given that the person is capable of carrying it out. There were also three predictors for behavioral intention: attitude, defined as one's affective judgments and opinions for the behavior in question; subjective norm, defined as one's "perceived social pressure" associated with displaying the behavior; and perceived behavioral control, defined as one's subjective judgment of whether performing the behavior is challenging or not (Ajzen, 1991, p. 188). This model hypothesized that to change one's behavior, it was necessary to change their attitude, subjective norm, and/or perceived behavioral

control of that behavior, which in turn would change their behavioral intention and hence their actual behavior outcome (Ajzen, 2011).

This model is particularly relevant to this study, as Ajzen has previously suggested in a 2011 work that "persuasive communications," which encompass the gain- and loss-framed appeals examined by this research, could change a person's actual behavior outcome if they target the three predictors for intention (p. 2). Previously, Parker et al. (1998) have investigated the applicability of this theoretical model in predicting aggressive driving behaviors. They discovered that drivers with more aggressive driving styles tended to hold more positive attitudes toward aggressive driving, perceive a greater degree of approval from their social circles (subjective norms), and have less control over their aggression—these predictors, in fact, all correlate to greater intention to drive aggressively, hence highlighting the interconnecting nature between the base predictors in the model, intention, and actual behavior outcome in aggressive driving (Parker et al., 1998).

Therefore, in situations where conducting naturalistic research is not possible, such as this study, it is practical to measure the change in the predictors of intention and intention change as indicators for the efficacy of persuasive messages on changing actual behavior.

2. Literature Review

After introducing the key concepts, this section reviews the debates, limitations, and past findings that are foundational to this study in the literature of (a) aggressive driving, (b) gain- and loss-framed appeals, and (c) attitude, intention, and behavior change.

2.1 The Aggressive Driving Literature

As mentioned earlier in section 1.1, both personal/dispositional and environmental factors can give rise to aggressive driving behaviors (Wickens et al., 2013). For this reason, many published articles have delved into the contributory and predictive factors of aggressive driving, such as age, gender, trait and state anger, environmental and situational factors, and many more (e.g., Krahé & Fenske, 2002; Lajunen & Parker, 2001; Nesbit et al., 2007). Among these studies, Shinar's (1998) model, presented in Figure 3, holistically explained how dispositional and environmental factors may interactively cause aggressive driving behaviors.
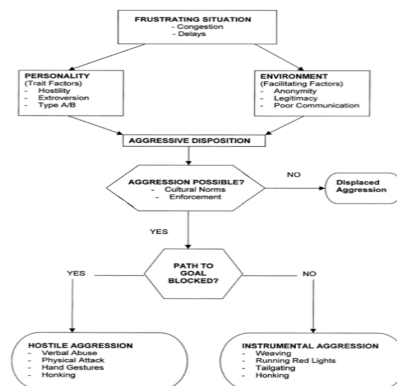
Figure 3. *The Model of Aggressive Driving (Shinar, 1998, p. 140)*

According to this model, "all aggressive behaviors are instigated by a frustrating situation, behavior, or event," which is called a frustration source (Shinar, 1998, p. 138). Then, environmental and personality factors will determine the driver's disposition to act aggressively.

This model is of great value for this study. Due to ethical concerns, it is not practical to instigate aggressive driving behaviors in a naturalistic setting. Nevertheless, it is possible to induce frustration, the root cause of aggressive driving, among participants with a piece of stimulus material delineating a stressful driving event with a salient frustration source and aggression-inductive environmental factors.

The frustration source mentioned by Shinar (1998) was road congestion. However, the scholarly community did not reach a consensus on whether this situation could legitimately lead to aggressive driving. While Hennessy & Wiesenthal (1997) found that aggressive driving occurred more frequently on roads of high congestion than on those of low congestion, Lajunen et al. (1999) later discovered that this variable did not correlate with an increase in aggressive driving behaviors. Eventually, Shinar & Compton (2004) offered a sound solution. Their research showed that although congestion itself could not trigger aggressive driving, when it was combined with a rush hour situation, where the urgency of time was made salient, it could accentuate aggressive driving behaviors (Shinar & Compton, 2004). Therefore, it is necessary to use road congestion and rush hour together as a combined frustration source in the stimulus material.

Shinar's (1998) model also revealed legitimacy and anonymity as the environmental factors that could give rise to aggressive driving. The former factor, legitimacy, was defined as a driver's perception of whether the situation is fair or not for themselves. If the driver perceived the situation as unfair, they would be more likely to drive aggressively (Shinar, 1998). The latter factor, anonymity, was defined as the state in which the driver "cannot be identified by others" (Ellison et al., 1995, p. 265). Being anonymous can undermine a driver's ability to control their aggressive driving behaviors (Novaco, 1998; Tasca, 2000). For instance, Ellison et al.'s (1995) field study discovered that driving in cars with tops-up (vs. tops-down) could increase horn-honking duration, which led researchers to assert that an enclosed automobile could reduce the drivers' "social identifiability" and, in turn, encourage aggressive driving behaviors (p. 266). This factor is worth mentioning because although many studies have studied anonymity as a situational factor, limited studies have looked at the anonymous nature of each aggressive driving behavior. In other words, some aggressive driving behaviors can be carried out anonymously in a car (e.g., running stop signs) while others can only be carried out while the driver is exposed to the external environment (e.g., shouting). One example of this approach is Craciun et al. (2017)'s research, which categorized aggressive driving behaviors into "direct aggression (e.g., speeding, tailgating, and honking)" and "indirect aggression (e.g., yelling and swearing)" (p. e50). To contribute to the literature, this study will continue Craciun et al.'s (2017) approach and examine if a message's persuasive power in creating intention change would differ between anonymous and non-anonymous aggressive driving behaviors.

2.2 The Gain- and Loss-Framed Appeals Literature

Researchers have investigated the relative persuasiveness of gain- and loss-framed appeals in a wide variety of contexts, including adopting animals (e.g., Kim, 2013), promoting pro-environmental behaviors (e.g., Davis, 1995; Kim & Kim, 2013), resolving human-coyote conflicts (e.g., Lu et al., 2016), promoting physical exercises (e.g., Cho et al., 2018), promoting COVID-19 vaccinations (e.g., Ye et al., 2021), and etc. (e.g., Ainiwaer et al., 2021; Apanovitch et al., 2003; Garcia-Retamero & Cokely, 2011; Goodall & Appiah, 2008; Rothman et al., 1999; Seo et al., 2013; Wyllie et al., 2015). However, there were certain ambiguities and limitations that required further investigation.

Firstly, this literature lacked internal consistency regarding which gain- or loss-

framed appeal was globally the most persuasive (Cho et al., 2018; Rothman & Salovey, 1997). While some studies found gain-framed messages (vs. loss-framed messages) to be the most effective (e.g., Cho et al., 2018; Kim & Kim, 2013), others found the opposite to be true (e.g., Davis, 1995; Ye et al., 2021). While some concluded that the relative persuasiveness of gain- and loss-framed appeals would vary from situation to situation (e.g., Apanovitch et al., 2003; Lu et al., 2016; Rothman et al., 1999), others found no difference between the persuasiveness of these two appeals (e.g., Ainiwaer et al., 2021; O'Keefe, 2011; O'Keefe & Jensen, 2006; Xu & Huang, 2020).

To account for this discordance, Rothman & Salovey (1997) proposed that whether an advocated behavior was prevention- or detection-based could influence the relative persuasiveness of gain- and loss-framed appeals. This theory postulated that gain-framed appeals (vs. loss-framed appeals) were most persuasive when advocating for prevention behaviors—i.e., behaviors that could reduce the risk of one getting ill in the future (Rothman & Salovey, 1997). Rothman & Salovey (1997) justified this theory as follows: according to the Prospect Theory (Tversky & Kahneman, 1981), since gain-framed appeals could prompt people to become risk-aversive, they were in favor of the risk-avoiding nature of prevention behaviors, hence enjoying a persuasive advantage. Nevertheless, since detection behaviors could expose one to the risk of knowing their abnormalities, these behaviors were riskier than prevention behaviors and, therefore, should be better promoted with loss-framed appeals, which were found to encourage risk-seeking behaviors (Rothman & Salovey, 1997; Tversky & Kahneman, 1981). While certain studies yielded congruent results with this theory (Garcia-Retamero & Cokely, 2011), others only partially supported (O'Keefe & Jensen, 2006) or did not support it at all (Ainiwaer et al., 2021). There has also been research suggesting that the relative persuasiveness of these two appeals was not affected by the objective riskiness of the advocated behavior but whether the audience would subjectively perceive it as risky or not (Rothman & Salovey, 1997). For instance, although loss-framed appeals were deemed relatively the most persuasive for promoting detection behaviors, if the audience regarded these behaviors as un-risky, their persuasive advantage would vanish (Rothman & Salovey, 1997; for empirical evidence, review Apanovitch et al., 2003). Therefore, there has yet to be a 'one-appeal-fits-all' conclusion in this literature, not even when behaviors were viewed separately as prevention- or detection-based.

Secondly, this discordance incubated another limitation: the limited case-to-case generalizability of established findings. In other words, the appeal that was found to be relatively the most persuasive when promoting behavior A would not necessarily be the most persuasive when advocating for behavior B due to differences in the nature of the two behaviors. This limitation could be found not only between the major categories of prevention and detection behaviors but also between each specific behavior. For instance, Goodall & Appiah (2008) called upon the literature to be cautious when applying results from other contexts to persuading smoking cessation, in that "the addictiveness of smoking, as well as the cultural and social factors[,]" has made this problem fairly unique, hence undermining the generalizability of past findings to this scenario (p. 126). Therefore, this limitation attenuated the referencing value of past studies focusing on other contexts when investigating the context of aggressive driving.

In fact, the context of precluding aggressive driving was understudied in this literature, with only a limited number of studies available (e.g., Chaurand et al., 2015; Craciun et al., 2017; Delhomme et al., 2010). One example is Chaurand et al.'s (2015) naturalistic research, which found gain-framed appeals to be the most effective for reducing the aggressive driving behavior of speeding. This result was explained by the regulatory focus theory, which divides people into promotion-focused individuals, who are motivated by "aspirations and accomplishments[,]" and prevention-focused individuals, who desire "responsibilities and safety" (Higgins, 1997, p. 1282). Since past research has discovered that promotion-focused individuals were more likely to drive aggressively (Craciun et al., 2017) and that gain-framed appeals (vs. loss-framed appeals)

were the most effective for targeting promotion-focused drivers (Teng et al., 2019), gain-framed appeals, therefore, were deemed to enjoy a persuasive advantage in tackling aggressive driving. However, Delhomme et al. (2010), despite yielding congruent results, stressed that they could not suggest the gain-framed appeals would consistently be more persuasive in this context because the frames they used were too "specific" to support generalization (Delhomme et al., 2010, p. 336). In other words, they feared that other elements rather than the gain-framed appeal itself may have contributed to the persuasive advantage of their gain-framed message. Hence, at present, one should not be too optimistic that Chaurand et al.'s (2015) findings can be successfully transferred to this study.

Eventually, although KS was an essential element of gain- and loss-framed appeals, limited studies in the literature have manipulated this variable. To the author's best knowledge, Apanovitch et al. (2003), de Bruijn et al. (2014), and Goodall & Appiah (2008) were some of the few researchers who considered this factor when framing messages. Yet, they have yet to reach an agreement upon which form (desirable vs. undesirable) and description (obtainment vs. removal) of the KS would best accentuate the persuasiveness of gain- and loss-framed appeals. When only considering studies that focused on aggressive driving in this literature, the discussion of KS was absent. Therefore, even though this literature suggested that gain-framed appeals may have been relatively the most persuasive for precluding aggressive driving, it could not determine which specific form out of the two gain-framed appeals would be the most persuasive.

To fulfill this research gap, this study would manipulate the KS and hence apply O'Keefe & Jensen's (2007) full 2 x 2 array when devising gain- and loss-framed messages.

2.3 The Attitude, Intention, and Behavior Change Literature

It is commonplace for studies in the gain- and loss-framed appeals literature to measure attitude change, intention change, and behavior change as indicators for the persuasiveness of a message. One example of this approach is Study 1 in Wyllie et al.'s (2015) research, which aimed to promote healthy behaviors among children. Before participants were exposed to the framed message, they were asked to report "the degree to which they enjoy eating food[,]" which was considered an attitude measure (Wyllie et al., 2015, p. 143). After seeing the message, participants reported their attitude again (Wyllie et al., 2015). This pretest-posttest approach measured participants' changes in attitude toward the advocated behavior due to exposure to the message, hence allowing the persuasiveness of the message to be visible.

However, the efficacy of attitude change in predicting intention change and the efficacy of intention change in predicting change in actual behavior have been debated. When penning The Theory of Planned Behavior, Ajzen (1991) suggested that regarding the specific context, "one [predictor] may be more important than the other and in fact, only one of the two predictors may be needed" (p. 185). In other words, while for some behaviors, measuring attitude change would be sufficient to predict intention change and hence behavior change, for other behaviors, all three predictors for intention or other predictors aside from attitude may be needed. Therefore, choosing the right predictors for the target context is vital for effectively predicting intention change and hence behavior change. According to Parker et al. (1998), in the context of aggressive driving, attitude, subjective norm, and perceived behavioral control were all statistically significant predictors for intention, and intention was a statistically significant predictor for actual behavior outcome. Therefore, it was deemed that all three predictors for intentions—i.e., attitude, subjective norm, and perceived behavioral control—would be effective in predicting intention change and hence behavior change in this study.

Nevertheless, there have been studies in the gain- and loss-framed literature that did not align with Parker et al.'s (1998) findings. For example, Ainiwaer et al. (2021) discovered "a disconnect between people's attitudes, intentions, and behavior." However,

their study was based on the context of cancer, which was different from aggressive driving. Since Parker et al. (1998) also focused on aggressive driving, their findings were believed to still have great referencing value for this study. However, if an individual, due to certain reasons, cannot implement and actualize the intention acquired from the message, then the intention change would lose its ability to predict behavior change (Ajzen, 2011). Considering how aggressive drivers were found to have poor self-control from driving aggressively (Parker et al., 1998), one should bear in mind that it may be possible that intention change fails to predict actual change in aggressive driving behaviors on the road.

2.4 The Current Study

After reviewing the foundational concepts, this study would use an exploratory approach to examine which form of gain- or loss-framed appeals would be most persuasive in changing drivers' attitudes and intentions to drive aggressively.

3. Pilot Study

3.1 Aim

To simulate a real-life driving situation that could trigger drivers' aggressive driving behaviors, this research aimed to create a hypothetical scripted scenario to induce their frustration. Therefore, a pilot study was conducted to test this scripted scenario on its efficacy to induce frustration and believability.

3.2 Participants

This pilot study looked for participants who met three criteria: (a) over 18 years old, (b) currently possessing a driver's license, and (c) having basic driving experience. As a result, 25 participants were recruited through mTurk, and they all completed the study ($N = 25$). Each participant was paid $0.50 for their participation.

3.3 Methodology

This pilot study used an online survey for data collection. Before the experiment, each participant signed and submitted their informed consent form, which specified the aim, instruction, recruitment criteria, and confidentiality of this study. Then, they were asked to read the following scenario.

> *Imagine you are driving on a highly congested road: unbelievably, your car did not drive out a great distance for 15 minutes. You are in the middle of the road, not too close to the next junction, not too far from it as well.*
>
> *Your work time starts in 10 minutes straight, and you have a morning meeting with your manager right after you get there, meaning you cannot be late, not even a minute. You glance at your GPS. It provides an approximate arrival time of within 7 minutes. You thought to yourself, "Even though it is close, if everything works just right, I can still arrive at work on-time and avoid being late in the meeting and being embarrassed (and potentially being scolded) when I enter the all-set meeting room."*
>
> *Now, you see, though afar, that the traffic light finally turns green! The road is moving. Your car finally moves! You are closer, closer and closer to the junction, and the light stays green!*
>
> *However, just as you are about to reach the junction and pass it,*

the cars in front of you suddenly slowed down for some unknown reason, even when the light is still green!

There isn't much time left for you...Because you know that parking, waiting for the elevator, and other stuff all need time...Time is slipping away...

To induce frustration, this scenario was carefully crafted regarding the underlying work reviewed in section 2.1. Firstly, inspired by Shinar & Compton (2004), the researcher set the background of this scenario to be a highly congested road during rush hour. Secondly, this scenario highlighted the illegitimacy of this driving experience by creating a contrast between the green traffic light and the inaction of the leading car, which was previously mentioned by Shinar (1998) to exemplify the concept of illegitimacy. This setting was also designed to further trigger participants' aggression. Seeing the traffic light turning green was deemed to be uplifting news amid this anxious time. However, the stagnating leading car in the next second could not only break apart participants' last hope to arrive to work on-time but also create an emotional arousal among them. Eventually, this scenario was written in a way to deliberately remind participants of the shortage of time. This feature was apparent from sentences like "*Time is slipping away*" and "*you know that parking...all need time.*"

After reading this scenario, participants responded to four questions. Question 1 examined participants' levels of frustration if they were to be involved in this scenario on a 0-4 scale (0 = not at all, 4 = very frustrated). Question 2, an open-ended, qualitative measure, asked participants to report the behaviors they would display if they were to be the driver in this scenario. Question 3 assessed the believability of this scenario on a 0-4 scale (0 = not at all, 4 = absolutely). Question 4, an optional question, asked participants to suggest possible improvements for this scenario (for the pro forma pilot study survey, see Appendix A).

For quantitative questions, the mean and standard deviation were reported. For qualitative questions, the analytical approaches were different. For Q2, irrelevant responses of the question were first filtered out to reduce demand characteristics of the participants, which was an inevitable drawback of collecting data via mTurk. The remaining responses were then analyzed to determine the efficacy of this scenario in triggering aggressive driving behaviors. For Q4, valuable feedback was first handpicked by the researcher and then used to propose an improvement checklist.

3.4 Results

Quantitative Data. On a 0-4 scale (0 = not at all, 4 = very), this scenario was effective in terms of inducing frustration among drivers (M = 3.1, SD = 0.7). Participants also found this scenario believable (M = 3.2, SD = 0.7).

Qualitative Data. To yield an instructive data set, responses in Q2 were filtered out if they (a) were irrelevant to the question (e.g., "INTEREST," "use a colon," "good," and "yes"), (b) failed to answer the question directly (e.g., "...every person shows different behaviors in different circumstances," "Accident," and "INTENSE"), and/or (c) were clearly not true (e.g., "none"—in that everyone should at least display some kinds of behaviors at any time). Responses that delineated emotions but not behaviors were not removed because emotions could show participants' underlying motivation to drive aggressively. Eventually, 10 responses were excluded (final n in Q2 = 15).

Among the remaining participants in Q2, 40% of them expressed that if they were to be the driver in this scenario, they would show dispositions or intentions to drive aggressively. These responses included "impatience," "sighing," "anxiety," "angry," and "annoyed." Some responses even matched with the aggressive driving behaviors listed in Tasca's (2000) research. The rest of the participants (60%) expressed that if they were to be the driver, they would display defensive driving behaviors (e.g., "keeping a safe distance

from the car in front of me, watching for pedestrians...driving at or below the speed limit"), alerting behaviors (e.g., "I will drive carefully"), and/or stress-releasing behaviors (e.g., "STAY CALM," "Peaceful Mind," and "lower anxiety..."). This implied that although the scenario failed to trigger aggressive driving intentions among all subjects, it at least effectively simulated a stressful driving experience that could potentially frustrate participants.

Then, based on participants' feedback in question 4, two areas of improvement were identified: using more intense diction and specifying that the lane inched and stopped like an infinite loop.

3.5 Discussions for Pilot Study

This pilot study ensured that the stimulus material would function as intended when inducing frustration among participants later in the main study. Therefore, it accentuated the internal validity of the main study. However, this pilot study had the following limitations.

Firstly, this study did not collect demographic information from participants. Therefore, whether participants' demographics have influenced their responses was unknown. Secondly, although the informed consent form has clearly started the recruitment criteria, this study recruited participants in a non-probability, self-selected fashion and did not apply actual screening tasks on participants, which may have attenuated the population representativeness of the sample and hence the population validity of the results. In addition, this study also had a small sample size due to the limited allocable resources at hand, which may have hindered the validity of the results. Furthermore, although the responses to open-ended questions were filtered to combat the limitation of the data collection method, the researcher's subjective interpretations when filtering data points may have introduced researcher bias and hence hindered the internal validity of the results.

These limitations would be taken into consideration when designing the main study to improve the quality of the research design.

3.6 Conclusion for Pilot Study

In conclusion, this scenario was deemed to have great believability and efficacy in inducing stress and frustration among participants. It could also directly trigger the intention among some participants to drive aggressively.

Regarding the improvement items, an updated version of the scenario was devised and attached below.

> *Imagine you are driving on a highly congested road: your car did not drive out a great distance for 15 minutes. You are in the middle of the road, neither too close to the next junction, nor too far from it as well.*
>
> *Your work time starts in 10 minutes, so the time is really short for you. Not to mention, you also have a morning meeting with your manager right after you get there, meaning you cannot be late, not even a minute. You glance at your GPS. It provides an approximate arrival time of "within 7 minutes." You say to yourself, "Even though it is close, if everything turns out just fine, I can still arrive at work on-time and avoid being late in the meeting and being embarrassed (and potentially being scolded) in front of other co-workers."*
>
> *Now, you see, though from afar, that the traffic light finally turns green! The cars in front of you start to move. You think to yourself, "Thank God! I can be on-time!"*
>
> *However, after moving out for an inch or two, the lane stops for*

some unknown reasons. You look toward the traffic light and think, "What? The light is still green!" Later, after about 15 seconds, it starts inching forward, and then it stops again. It inches...it stops...it inches...and it stops...This entire thing seems like an infinite loop...

       However, there isn't much time left for you...Two minutes already passed, and the clock is still ticking. You know that parking, waiting for the elevator, and other preparations all need time and that completing these within 1 minute is rarely possible...

       Time is slipping away...What you do now is very important...

This new version used (a) more intense diction to emphasize the deficiency of time (e.g., "*the time is really short for you,*" "*rarely possible*," and "*what you do now is very important*"), (b) more inner dialogues to guide participants to imagine themselves being in this scenario, (c) a new plot indicating that the lane was inching forward and stopping like an infinite loop. The latter change is particularly important, as it is more representative of a rush-hour condition and, therefore, can further enhance the realism and believability of this scenario.

       Aside from these changes, the structure and the core of this scenario remained the same. Therefore, the results in the pilot study were deemed transferrable to this new version. This updated version will be used in the main study as a piece of stimulus material to measure participants' pre-message aggressive driving intention.

4. Main Study

4.1 Aim and Participants

The main study used a pretest-posttest approach to investigate which gain- or loss-framed message would be the most effective in changing drivers' attitudes toward aggressive driving and intentions to drive aggressively.

       To achieve this, this study looked for participants who (a) were at least 18 years old, (b) each possessed a driver's license, (c) had basic driving experience, and (d) displayed aggressive driving behaviors.

       As a result, 154 participants were recruited through mTurk. This time, an eligibility test was carried out to eliminate participants who did not meet criterion D. Moreover, participants who did not complete the study or did not pass the comprehension task embedded in the survey were also screened out. The final sample consisted of 77 participants, who were each paid $ 0.50 for participation.

4.2 Methodology

4.2.1 Variables

The independent variable (IV) of this study was the persuasive messages. There were a total of five messages used in this study: one unframed message and four framed messages. The unframed message was written with the least possible wordings and modifiers to increase its ability to serve as a control. Among framed messages, half were gain-framed, and the other half were loss-framed. Messages were framed with either the desirable KS of "turning out safe" or the undesirable KS of "being involved in a lethal crash." The word count did not vary significantly among framed messages.

       Table 1 displays all five messages and whether they were considered unframed, gain-framed, or loss-framed.

Table 1. *The Persuasive Messages Used in This Study*

Message 1 (**Unframed**; 2 words): "Drive safely."		
	Desirable KS: "Turn out safe"	Undesirable KS: "Involve in a lethal crash"
KS being obtained	Message 2 (**Gain-Framed**; 20 words) *"If you drive safely, you will **increase** the likelihood of turning out safe for yourself, your passengers, and other drivers."*	Message 5 (**Loss-Framed**; 25 words) *"If you do not drive safely, you will **increase** the likelihood of being involved in such lethal crashes for yourself, your passengers, and other drivers."*
KS being removed	Message 4 (**Loss-Framed**; 22 words) *"If you do not drive safely, you will **decrease** the likelihood of turning out safe for yourself, your passengers, and other drivers."*	Message 3 (**Gain-Framed**; 23 words) *"If you drive safely, you will **decrease** the likelihood of being involved in such lethal crashes for yourself, your passengers, and other drivers."*

In addition, this study collected data on three dependent variables (DV) to determine the persuasiveness of the messages: attitude change (DV 1), intention change (DV 2), and participants' evaluations of the advertisement (DV 3). Attitude but not subjective norm or perceived behavioral control was selected as the predictor for intention because it was initially thought that these messages were more relevant to changing aggressive driving beliefs and attitudes. The detailed procedures for measuring these DVs were disclosed in section 4.2.3.

4.2.2 Stimulus Materials and Testing Conditions

Each message formed a testing condition, resulting in a total of five conditions. In each condition, participants were presented with an advertisement to watch. These advertisements were curated based on the "Don't Drive Like You're Five: Road Rage" video (Honda, 2016) as follows:

a) The "ROAD RAGE CAN BE destructive" message at 0:15 was replaced by "AGGRESSIVE DRIVING CAN BE destructive" to clarify the behavior in focus (Appendix B1);

b) The "don't drive like you're five" slogan at 0:18 was removed;

c) In each duplicate of the edited video, a message from Table 1 was added to the end for a fixed duration of 5 seconds (Appendix B2).

The result was five advertisements, each with the same duration of 22 seconds, that were completely identical to each other except for the message at the end (see Appendix C for all advertisements).

4.2.3 Procedures

All participants gave their informed consent before participation. Then, a revised Aggressive Driving Scale (rADS) was given to them as a preliminary eligibility test.

The rADS was developed by adapting Krahé & Fenske's (2002) Aggressive Driving Scale (ADS) to (a) shorten the ADS into a more convenient length for online survey, (b) avoid repetitive questions, (c) focus primarily on assessing aggressive driving behaviors, and (d) expand the scope of this questionnaire by adding new questions based on Tasca's (2000) aggressive driving behavior list. As a result, the rADS encompassed 11 questions: three unchanged questions from ADS, five questions adapted from ADS with partial changes, and three new questions (see Appendix D for rADS). In each question, participants rated themselves on a 0-4 scale (0 = never, 4 = often). Then, they reported their total score by summing the scores from each question. Out of the maximum score of 44, participants who scored less than 11 were screened out because aggressive driving was not a problem for them, hence improving the population representativeness of the sample. Participants who reported over 44, the maximum boundary, were also screened out

because they either made a mistake when reporting their results or did not perform the preliminary test attentively, hence cementing the quality of the sample.

Eligible participants were randomly assigned to one of the five conditions: message 1 ($n = 17$), message 2 ($n = 15$), message 3 ($n = 14$), message 4 ($n = 16$), and message 5 ($n = 15$). Each condition consisted of three sections: the pre-message test, the advertisement, and the post-message test.

The pre-message test consisted of five questions. The first three questions measured participants' attitudes toward aggressive driving behaviors on a 1-5 scale (1 = no, 5 = yes). Question 1 (Q1), "Do you perceive aggressive driving behaviors as unacceptable behaviors," examined participants' general attitudes toward aggressive driving. Question 2 (Q2), "Do you think aggressive driving is an issue that should be solved," examined their awareness of aggressive driving being a social issue. Question 3 (Q3), "Do you think aggressive driving behaviors, no matter if they are displayed by yourself or others, will affect your safety," measured the extent to which the participants regarded aggressive driving as personally relevant.

Then, participants read the updated scenario devised from the pilot study (section 3.6). Meanwhile, a timer was set to 30 seconds to prevent them from skipping this reading task. Afterward, participants were asked to imagine themselves being in this situation and rate their likelihood of displaying anonymous (Q4) and non-anonymous (Q5) aggressive driving behaviors on a scale of 1-5 (1 = definitely not displaying, 5 = definitely will). To ward off potential perplexities, participants were given a list that distinguished which aggressive driving behaviors were considered anonymous and which were considered non-anonymous (see Appendix E).

After this pre-message test, participants watched the advertisement that matched with their assigned condition. For instance, those assigned to the message 1 condition were only given the advertisement containing message 1 to watch, and so on. Likewise, a timer was set to 10 seconds to prevent them from skipping this task. To ensure that participants paid attention to the video, they were required to respond to a comprehension question on the next page: "Did the kids punch down the buildings at the end of the video?" Participants who did not respond "Yes," the correct answer, were screened out. This design was inspired by Chmielewski & Kucker (2019) to offset the concerning sample quality on mTurk.

Afterward, participants proceeded to the post-message test. They were asked to submit their responses again to Q1, Q2, Q3, Q4, and Q5: respectively being Q6, Q7, Q8, Q9 and Q10. Instead of showing the scenario again, a scripted instruction separated questions that measured post-message attitudes (Q6, Q7, and Q8) from those that measured post-message intentions (Q9 and Q10). Then, participants evaluated the advertisement they watched based on its effectiveness in raising awareness (Q11), ability to motivate safe driving (Q12), memorability (Q13), likability (Q14), and word-of-mouth (Q15).

Eventually, before completing the experiment, participants reported their demographic information (age in Q16; gender in Q17).

4.2.4 Statistical Analyses

To test the general effect of messages on attitude change (DV 1), an attitude change variable was created by averaging participants' responses among the questions that measured attitude, hence generating a pre-message and a post-message mean score on attitude for each condition. Then, a repeated measures ANOVA (Analysis of Variance) test was performed to look at whether there was a statistically significant effect of the message on participants' attitude change for aggressive driving behaviors. The same procedure was used to analyze DV 2, intention change. Eventually, for more thorough analyses, a repeated measures t-test was also performed for each specific measure in attitude (DV 1) and intention change (DV 2). Noteworthily, instead of using the post-message mean, this study would only use the t-values for between-condition comparison lest the participant

variability between the five conditions would impact the results.

To analyze participants' evaluations of the advertisement (DV 3), the mean and standard deviation were calculated for each message condition in each DV 3 measure. Then, a one-way ANOVA test was calculated for each DV 3 measure to examine whether there was a statistically significant effect of the message on participants' evaluations of the advertisement in that specific measure. Eventually, to examine the general effect of the message on advertisement evaluation (DV 3), an evaluation variable was created by averaging participants' responses among all DV 3 questions, therefore generating a mean evaluation score for each advertisement. These scores would then be compared to determine which advertisement was most positively evaluated by the participants.

4.3 Results

4.3.1 Demographics
57.14% of the participants reported their gender as male, and 42.86% of the participants reported their gender as female. No other choices were reported.

63.64% of the participants, the majority, reported their age as 25-34 years old. 19.48% of the participants reported being 35-44 years old; 9.09% reported being 45-54 years old; 6.49% reported being 18-24 years old; 1.30% reported being 55-64 years old. None of the participants reported being under 18 years old or being 65 or older.

4.3.2 Attitude Change (DV 1)
A repeated measures ANOVA test examined the effect of message on attitude change. This effect was not statistically significant ($F(4, 72) = 0.91$, $p = .47$).

Table 2 reports the results of the repeated measures t-tests. As a result, message 1 had a marginally significant effect on persuading participants to perceive aggressive driving as unacceptable ($t(16) = -1.57$, $p = .07$); message 4, despite not having statistically significant effect, had relatively the strongest effect on raising participants' awareness of aggressive driving as a social issue ($t(15) = -1.15$, $p = .14$); and message 2, despite not creating statistically significant effect, had relatively the strongest power on persuading participants to perceive aggressive driving as personally relevant ($t(14) = -1.00$, $p = .17$).

Eventually, Figure 4 presents the pre-message and post-message mean of each message condition after averaging participants' responses in all DV 1 questions. It appeared that message 4 may have been the most effective message for attitude change. This implied that if the sample size had been larger and more representative, this trend may have been discovered. However, it requires validation from future studies.

Table 2. *Results of Repeated Measures T-Tests in Attitude Change (DV 1)[1]*

Measures	Condition	Pre-Message Test Mean	Post-Message Test Mean	T-Value	Degree of Freedom	One-Sided P-Value
General perception of aggressive driving behaviors	**Message 1**	4.00	4.29	**-1.571**	16	.068
	Message 2	3.87	3.93	-.323	14	.376
	Message 3	3.93	3.64	1.170	13	.132
	Message 4	4.19	4.31	-1.464	15	.082
	Message 5	3.80	3.80	.000	14	.500
Awareness of aggressive driving behaviors as an issue	Message 1	3.94	3.71	1.000	16	.166
	Message 2	3.80	3.80	.000	14	.500
	Message 3	3.79	3.71	.234	13	.409
	Message 4	3.81	4.00	**-1.145**	15	.135
	Message 5	4.00	3.73	1.000	14	.167

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[1] The most persuasive message in each question has been bolded.

Measures	Condition	Pre-Message Test Mean	Post-Message Test Mean	T-Value	Degree of Freedom	One-Sided P-Value
Personal relevance with aggressive driving behaviors	Message 1	4.06	3.88	1.376	16	.094
	Message 2	3.93	4.07	**-1.000**	14	.167
	Message 3	4.00	3.79	.763	13	.230
	Message 4	4.25	4.31	-.565	15	.290
	Message 5	3.73	3.60	.807	14	.217
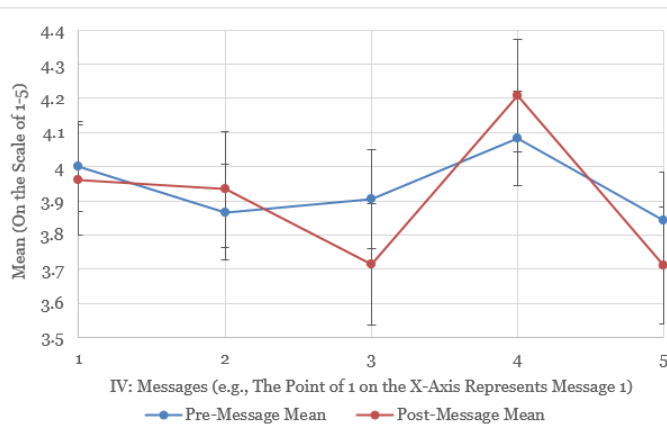
Figure 4. *A Comparison of the Pre-Message and Post-Message Mean of Each Message in DV 1 (Error Bar: Standard Error)[2]*

4.3.3 Intention Change (DV 2)

A repeated measures ANOVA found the effect of message on intention change to be statistically significant ($F(4, 72) = 2.81$, $p = .03$). Post-hoc analyses found message 3 to be driving this effect ($p = .003$)—i.e., to be the most persuasive message among all five.

The repeated measures t-tests in Table 3 also revealed message 3 as the most effective message in both DV 2 questions: it had a marginally significant effect on precluding participants' intentions to perform anonymous ($t(13) = 1.59$, $p = .07$) aggressive driving behaviors and also a statistically significant effect on precluding their intentions to perform non-anonymous aggressive driving behaviors ($t(13) = 1.89$, $p = .04$).

After averaging participants' responses in both DV 2 questions, Figure 5 graphs the processed data result. From this graph, it was evident that message 3, again, was the most persuasive message in this study to reduce drivers' intentions to drive aggressively.

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[2] The farther away the post-message point was positioned *above* the pre-message point, the more effective the message in persuading participants to have negative attitudes toward aggressive driving.

Table 3. *Results of Repeated Measures T-Tests in Intention Change (DV 2)[3]*

Measures	Condition	Pre-Test Mean	Post-Test Mean	T-value	Degree of Freedom	One-Sided P-value
Anonymity Aggressive Driving Behaviors	Message 1	4.18	4.24	-.436	16	.334
	Message 2	3.87	3.93	-.323	14	.376
	Message 3	3.86	3.50	**1.587**	13	.068
	Message 4	3.94	4.06	-1.464	15	.082
	Message 5	3.93	4.00	-.367	14	.360
Non-Anonymity Aggressive Driving Behaviors	Message 1	3.82	4.00	-1.144	16	.135
	Message 2	3.53	3.73	-1.146	14	.136
	Message 3	4.00	3.57	**1.883**	13	.041
	Message 4	3.94	3.88	1.000	15	.167
	Message 5	3.87	3.73	.619	14	.273
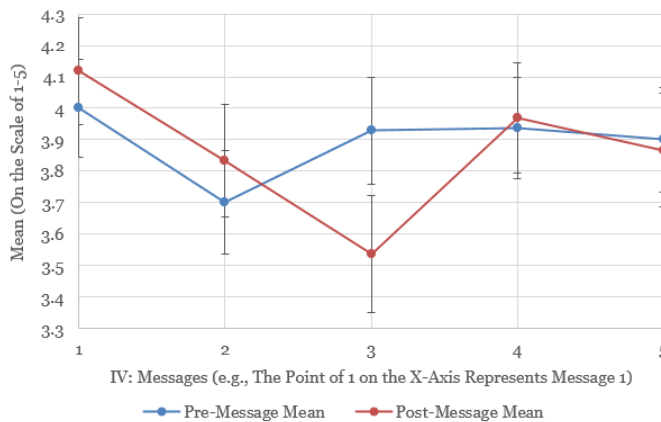
Figure 5. *A Comparison of the Pre-Message and Post-Message Mean of Each Message in DV 2 (Error Bar: Standard Error)[4]*

4.3.4 Advertisement Evaluation (DV 3)

Multiple one-way ANOVA tests revealed no statistically significant effect of the message on the advertisement's effectiveness in raising awareness of aggressive driving ($F(4, 72) = 0.83$, $p = .51$), ability to motivate safe driving ($F(4, 72) = 0.27$, $p = .89$), memorability ($F(4, 72) = 0.71$, $p = .59$), likability ($F(4, 72) = 0.63$, $p = .64$), and word-of-mouth ($F(4, 72) = 1.40$, $p = .24$).

Again, the small sample size may have inhibited the discovery of significant results. Therefore, descriptive statistics were reported in Table 4. As a result, message 4 may have been the most effective message to raise awareness ($M = 4.3$, $SD = 0.7$). Message 1 may have been the most effective message to motivate safe driving behaviors ($M = 4.1$, $SD = 0.9$) and improve the memorability of the advertisement ($M = 4.1$, $SD = 0.7$). Eventually, message 3 may have been the most effective message in improving the likability ($M = 4.4$, $SD = 0.9$) and word-of-mouth ($M = 4.3$, $SD = 0.5$) of the advertisement.

After averaging participants' responses across all DV 3 questions, Figure 6 reveals that the advertisement containing message 1 may have generally received the most

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[3] The most persuasive message in each question has been bolded.

[4] The farther away the post-message point was positioned *below* the pre-message point, the more effective the message in precluding aggressive driving intention.

positive evaluation from the participants, while the advertisement with message 5 may have received the worst evaluation.

Therefore, in summary, while message 1, message 3, and message 4 may have been the most effective messages in improving participants' evaluations of the advertisements on different DV 3 measures, message 1 may have been the most effective in improving participants' general positive evaluations of the advertisement. However, due to the insignificant ANOVA results, these trends require further examination.

Table 4. *Descriptive Statistics in Advertisement Evaluation (DV 3)[5]*

Measures	Condition	Mean	Standard Deviation
Effectiveness in raising awareness	Message 1	4.0588	.65865
	Message 2	3.9333	.70373
	Message 3	3.9286	.47463
	Message 4	**4.2500**	.68313
	Message 5	3.8667	.74322
Ability to motivate participants to drive safely	**Message 1**	**4.1176**	.85749
	Message 2	4.0667	.70373
	Message 3	3.8571	.66299
	Message 4	4.0625	.77190
	Message 5	4.0000	.65465
Memorability	**Message 1**	**4.1176**	.69663
	Message 2	3.8667	.74322
	Message 3	3.9286	.47463
	Message 4	4.0000	.63246
	Message 5	3.7333	.79881
Rate of being liked by the target market	Message 1	4.2353	.66421
	Message 2	4.0000	.65465
	Message 3	**4.3571**	.92878
	Message 4	4.1875	.91059
	Message 5	4.0000	.53452
Word-of-mouth	Message 1	4.0588	.65865
	Message 2	3.9333	.70373
	Message 3	**4.2857**	.46881
	Message 4	3.9375	.68007
	Message 5	3.7333	.70373
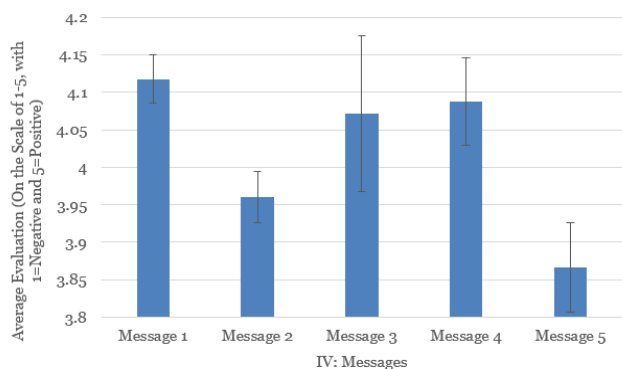
Figure 6. *The Comparison of the Mean of Each Message in DV 3 (Error Bar: Standard Error)*

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[5] The message with the highest mean value in each question has been bolded.

5. Discussion

5.1 Summary and Discussion of the Findings

Using a pretest-posttest approach, this study examined the relative persuasiveness of gain- and loss-framed messages on changing drivers' attitudes toward aggressive driving and intentions to drive aggressively.

As a result, the level of attitude change (DV 1) did not have statistically significant differences between each message condition, hence revealing that none of the five messages enjoyed a persuasive advantage in attitude change. However, when comparing the pre-message and post-message mean scores of each condition, it was deemed that message 4 (loss-framed, removing a desirable KS) may have been the most persuasive message in attitude change. However, due to the statistically insignificant effect, this result can only be seen as a possible trend, not a definite conclusion.

Then, this study discovered that the level of intention change (DV 2) had statistically significant differences between each message condition, with message 3, a gain-framed message describing the removal of an undesirable KS, being the most persuasive message. Repeated measures t-tests in Table 3 also found message 3 to be the most persuasive message in reducing drivers' intentions to perform either anonymous or non-anonymous aggressive driving behaviors.

Eventually, this study did not find significant interactions between messages and each measure of advertisement evaluation (DV 3). However, when comparing the mean score of each condition, message 4 (loss-framed, removing a desirable KS) may have been the most effective message to raise awareness; message 1 (unframed) may have been the most effective in motivating drivers to drive safely and the improving the memorability of the advertisement; message 3 (gain-framed, removing an undesirable KS) may have been the most effective message in improving the likeability and word-of-mouth of the advertisement. Overall, it was found that message 1 (unframed) may have helped the advertisement receive the most positive audience evaluation, followed by message 4 (loss-framed, removing a desirable KS), message 3 (gain-framed, removing an undesirable KS), message 2 (gain-framed, obtaining a desirable KS), and message 5 (loss-framed, obtaining an undesirable KS). However, these trends need to be validated by future studies.

The result that message 3, a gain-framed message, is the most effective in reducing aggressive driving intention aligns with Chaurand et al.'s (2015) and Delhomme et al.'s (2010) results. However, the fact that message 3 emphasized the removal of an undesirable KS contradicts (a) O'Keefe & Jensen's (2006) prediction that the persuasiveness of a gain-framed message will be attenuated when describing the removal of an undesirable KS, (b) de Brujin et al.'s (2014) finding that a loss-framed message concerned with the obtainment of an undesirable KS was relatively the most persuasive, and (c) Goodall & Appiah's (2008) finding that gain-framed messages with a desirable KS and an undesirable KS did not differ in persuasiveness.

To account for these discordances, it is first necessary to examine the differences between the KS used in this study and those used by Goodall & Appiah (2008). To promote smoking cessation, Goodall & Appiah (2008) used two pairs of KS in their gain-framed messages: one pair was "mouth diseases" (undesirable) and "improv[ing] your health and appearance" (desirable), and the other pair was "breathing difficulties" (undesirable) and "breathe easier" (desirable; p. 121). In comparison, the KS used in this study were "fatal crashes" (undesirable) and "turning out safe" (desirable). Although the desirable KS of this study and those of Goodall & Appiah (2008) were similar in perceived severity, this study used a noticeably more severe and alarming undesirable KS than did Goodall & Appiah (2008). Therefore, the more intimidating nature of the undesirable KS in message 3 of this study may have shaped the suggestion to halt aggressive driving to appear more appealing, urgent, and necessary to the participants, therefore allowing the difference in

persuasiveness between the two forms of gain-framed appeals to be visible.

Following this logic, one may start to doubt the advantage of message 3 over message 5, which, despite being a loss-framed message, also involved the removal of an undesirable KS. To explain this contradiction, it is necessary to consider the difference between the nature of gain-framed and loss-framed appeals. Recent research by Cho et al. (2018) discovered that gain-framed appeals (vs. loss-framed appeals) could relatively increase subjects' perceived benefits in the advocated behavior, which could, in turn, influence behavior "adoption" (p. 830). This means that participants may have perceived a greater incentive to stop aggressive driving behaviors when they read message 3 (gain-framed) than when they saw message 5 (loss-framed), despite both having the same KS. Another way to reason is that since message 3 started with "if you drive safely," it may have pointed out a clearer direction of behavior change for participants than did message 5, which began with "if you do not drive safely."

Indeed, the result that the messages had a statistically significant effect on intention change but an insignificant effect on attitude change was unexpected. Although the cause of this situation was unknown, this study would offer two explanations.

Firstly, as mentioned in the literature review, The Theory of Planned Behavior suggested that which and how many predictors the researcher should use would differ between contexts (Ajzen, 1991). Therefore, despite contradicting Parker et al.'s (1998) findings, there is a possibility that attitude may have not been the effective predictor for intention in this study. For instance, it may have been the case that subjective norm was the effective predictor for intention, considering that the gain- and loss-framed messages in this study have emphasized the social pressure of not driving safely (e.g., "...for yourself, your passengers, and other drivers."). However, this explanation could only be seen as a conjecture, given that no linear regression tests were performed between the variable of attitude change and intention change. In addition, since this pressure was made salient in all framed messages as a control, one may expect this factor to have trivial to no effect on subjective norm change between the experimental groups, not to mention that the subjective norm was not measured as a DV in this study.

The second explanation was that the recruitment platform used in this study, namely mTurk, may have hindered the replication of Parker et al.'s (1998) results. In 2019, researchers Chmielewski and Kucker discovered that the data collected from mTurk was subject to having poor quality and, therefore, could prevent the study from retaining previous results in the literature. Therefore, it may have been the case that attitude was an effective predictor for intention, but the limitation of the research design has rendered it ineffective in this study. Nevertheless, determining which explanation was valid requires future studies to replicate this study again with a linear regression test performed between the attitude change and intention change variables while, preferably, collecting data through in-person means.

5.2 Limitations

Although this study found a gain-framed message describing the removal of an undesirable KS to be the most persuasive message, it remains challenging to argue that this form of gain-framed appeal would consistently be the most persuasive in precluding aggressive driving. This reservation was largely due to the limitations of this study.

5.2.1 Sampling Bias

Inspired by the limitations in the pilot study, the main study included a screening task to improve the representativeness of the sample. However, the efficacy and validity of this screening task required further examination. Because the rADS scale, despite being produced upon the well-validated ADS instrumentality (Krahé & Fenske, 2002), did not receive its own validity check. Furthermore, the efficacy of using the threshold of 11 marks to screen out participants was not statistically tested. Therefore, the actual difference in

life between the levels of aggression displayed by participants who scored below 11 and those displayed by participants who scored 11 and above was unknown. Moreover, for ethical reasons, this study did not ask participants to upload their driver's licenses to verify their identities as drivers, which may have limited the population representativeness of the sample.

In addition, the self-reporting nature of this screening task may have hindered its internal validity. As mentioned earlier, aggressive drivers may not perceive their driving styles as aggressive (Miles & Johnson, 2003). Therefore, this lack of awareness may have caused them to report their rADS score in a fashion that did not represent their actual driving behaviors. Alternatively, some subjects may have felt the need to establish a socially desirable image when answering the questions, thereby causing their responses to be less representative of their aggressive driving behaviors in life and, hence, further hindering the population representativeness of the sample.

Furthermore, an unexpected issue emerged in the execution of the screening task. Since the software could only detect numerical inputs, some participants submitted non-numerical responses (e.g., words and letters) and were able to trespass the screening task and move on to the subsequent sections. This may have jeopardized the quality of the sample and decreased the population validity of the results.

Lastly, the sample size of this study was relatively small, with less than 20 people in each condition. This was considered a limitation, as it may have prevented statistically significant results from being discovered.

5.2.2 Methodological Constraints

One methodological constraint in this study was the self-reporting nature of the pre-message test and post-message test. This inevitably opened possibilities for demand characteristics to emerge, which may have hindered the validity of the results. In fact, the choice to use mTurk to collect data may have reduced the data quality of this study (Chmielewski & Kucker, 2019), as the incentive-driven nature of this platform may have caused participants to value completing the tasks more important than attentively engaging in the tasks and offering thoughtful responses.

Another constraint was found in the pretest-posttest approach. In this study, the only design that separated the pre-message test from the post-message test was a 22-second advertisement. In real life, it is unlikely for a driver to accurately 'prophesy' the time when they would drive aggressively and remind themselves to read a persuasive message 22 seconds in advance. Therefore, the fact that the post-message test was conducted almost immediately after the presentation of the message hindered the mundane realism of this study.

Furthermore, similar to Delhomme et al. (2010), this study reserves making the generalization that a gain-framed *appeal* based on the removal of an undesirable KS will consistently be the most persuasive among all gain- and loss-framed appeals in the context of precluding aggressive driving behaviors. Because other factors in *message* 3 may have also contributed to its persuasive advantage. There were four elements involved in the framed messages of this study: (a) compliance or noncompliance, (b) the advocated behavior, (c) the consequence of action (KS desirability & being obtained or removed), and (d) the people involved in the consequence. Although elements A and B were not subject to drastic change in the same context, elements C and D could vary greatly. For example, while this study used safety as the theme of consequence, Chaurand et al. (2015), who focused on the issue of highway speeding (an aggressive driving behavior), used "fuel consumption" as one of their themes (p. 42). Therefore, the persuasive advantage of message 3 in this study may have been a result of a collective power between all four elements rather than the sole power of the appeal, which means that it is unknown whether changing elements C and D in message 3 would alter its relative persuasiveness with other gain- and loss-framed messages.

In addition, since this study did not include a group that received no messages, it

is hard to determine the role of the advertisement video in the relative persuasiveness of gain- and loss-framed messages. Specifically, it was ambiguous whether the persuasive advantage of message 3 was facilitated by the contents in the video or not.

Eventually, this research did not collect actual behavior change in a naturalistic setting as a DV. This implied that the results of this study could only be used to extrapolate but not conclude what would happen when gain- and loss-framed messages were applied to real life to prevent aggressive driving behaviors.

5.3 Suggestions for Future Research

To further extend the boundary of this field, future research is encouraged to take on the following approaches.

Firstly, the writer recognizes the importance of replication and therefore encourages future researchers to do so. However, when replicating this study, it is strongly suggested that researchers should improve the methodology by (a) testing with a larger and more representative sample, (b) testing the validity and efficacy of the rADS instrumentality, (c) designing a stronger survey system that ensures proper execution of the screening task, (d) measuring actual behavior change as a dependent variable, (e) designing a testing condition with no messages presented, and (f) collect data via in-person means instead of mTurk or other online platforms.

The second approach requires more creativity: the researchers are welcome to use this study as a foundational work to discover more factors that may influence the efficacy of gain- and loss-framed appeals in precluding aggressive driving. For example, they can explore whether (a) the theme of consequence (death, injury, etc.), (b) expanding the population affected by the consequence (i.e., making the social pressure salient), and (c) the medium that presents the message (e.g., videos, posters, radio stations) would impact persuasion. With more factors investigated, it will increase the possibility for the field to find a form of gain- or loss-framed appeal to consistently be the most persuasive in preventing aggressive driving behaviors. For this reason, the author suggests future scholars to include the desirability and description of the KS, the theme of consequence, and other elements that are deemed contributory to the persuasiveness of the message in the abstract of their work (e.g., gain-framed appeal; the removal of an undesirable KS; theme: fatal crash; people involved: driver, passenger, other road users; medium: video ad), instead of simply mentioning whether the message was gain- or loss-framed. This can emphasize the importance of other elements in determining the persuasiveness of a message and ensure that even though the messages of one study may be too specific, they can still have referencing values for future researchers.

Eventually, future researchers are encouraged to examine two additional topics. Firstly, it is essential to understand the long-term efficacy of gain- and loss-framed appeals on changing aggressive driving attitudes, intentions, and behaviors. Secondly, researchers should investigate whether these appeals could also preclude drivers' intentions to perform displaced aggression due to frustrating driving experiences. According to Shinar's (1998) model, when a driver's intention to drive aggressively is inhibited in the immediate moment, they may express their aggression in a different context later in life—a phenomenon termed "displaced aggression" (p. 140). For this reason, Shinar (1998) suggested that "public information campaigns may have limited value" in solving aggressive driving (p. 158). However, neither Shinar's (1998) study nor this one has empirically tested the effect of persuasive messages on precluding displaced aggression acquired from frustrating driving experiences. This topic is crucial for investigation because although persuasive messages can psychologically prevent drivers from driving aggressively at present, if they decide to express their aggression toward other people, through other means, and at a later time, a new social problem will emerge.

6. Conclusion

This study identified a gap between the gain- and loss-framed appeals literature and the aggressive driving literature. As a result, a gain-framed message describing the removal of an undesirable KS (theme: fatal crash; people involved: driver, passenger, other road users; medium: video ad) enjoyed a persuasive advantage in changing drivers' behavioral intentions. However, none of the messages had a persuasive advantage in attitude change, and none of them had a persuasive advantage in increasing participants' ratings of the advertisement on each evaluative measure.

When thinking about marketing practitioners, one may automatically assume their responsibilities are to boost sales and promote products. Nevertheless, this assumption is not well-rounded. In fact, many consider promoting safe and healthy behaviors as a vital part of their marketing pursuit. This study is a manifestation of such social responsibilities of marketers, where knowledge meets application, application fosters change-making, and change-making vitalizes the world.

For social ventures, non-governmental organizations, policymakers, transportation bureaus, and other entities aiming to solve aggressive driving, this study may have presented a cost-saving and efficient solution, such that the presence of few words could effectively mitigate a driver's intention to drive aggressively. Nevertheless, it is quite early to be fully confident with this discovery, as there are still blank areas in this field that await future explorations.

This study has been one of the first breezes to cool down the roads filled with overt aggression. With more research coming, this study shall and will not be the last breeze.

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Appendices

Appendix A: Pilot Study Survey Pro Forma

Page 1: Aggressive Driving Research: Pilot Study

Hello!

This is a pilot study of a primary research investigating behaviors related to Aggressive Driving.

The instruction is simple. You will be presented an on-road scenario. After reading this material, you will be asked four questions. Please complete these questions honestly based on your true feelings.

To be noticed, in order to be a part of this study, you have to be ***over 18 years old***, have to ***possess a driver's license***, and have to ***possess basic driving experiences on the road***. If you ***DO NOT*** fit in these criteria, please ***exit this form.***

Other information aside from your responses will not be collected. Your responses will be used for the purpose of this pilot study ***only***.

Sincerely appreciate your participation.

* Indicates required question

Type "***Yes***" in the textbox below to certify that you fit in the participant requirements and that you participate in this study with your own will. *

_____

Page 2: The On-Road Scenario

Carefully read through the scenario below:

Imagine you are driving on a highly congested road: unbelievably, your car did not drive out a great distance for 15 minutes. You are in the middle of the road, not too close to the next junction, not too far from it as well.

Your work time starts in 10 minutes straight, and you have a morning meeting with your manager right after you get there, meaning you cannot be late, not even a minute. You glance at your GPS. It provides an approximate arrival time of within 7

minutes. You thought to yourself, "Even though it is close, if everything works just right, I can still arrive at work on-time and avoid being late in the meeting and being embarrassed (and potentially being scolded) when I enter the all-set meeting room."

Now, you see, though afar, that the traffic light finally turns green! The road is moving. Your car finally moves! You are closer, closer and closer to the junction, and the light stays green!

However, just as you are about to reach the junction and pass it, the cars in front of you suddenly slowed down for some unknown reason, even when the light is still green!

There isn't much time left for you…Because you know that parking, waiting for the elevator, and other stuff all need time…Time is slipping away…

Page 3: Survey

After reading the material, complete the following questions honestly based on your first impressions.

1. Rate the level of frustration you will experience if you are in this situation. *
(Mark only one oval.)

No frustration at all.   Very frustrated.
         0   1   2   3   4

2. If you are driving in this situation, what behavior will you most likely to display? (If you want to write multiple types of behavior, use a colon ";" to separate between each behavior.) *

3. Rate the extent to which this scenario is believable to you. *
(Mark only one oval.)

   No at all.   Absolutely
         0   1   2   3   4

4. If you are asked to suggest one, or two, things of how this scenario can improve to become more believable or more relevant to the context of aggressive driving, what will these be? (Use a colon ";" to separate your suggestions if you are planning to write multiple things.)

Appendix B: Steps to Curate the Advertisements
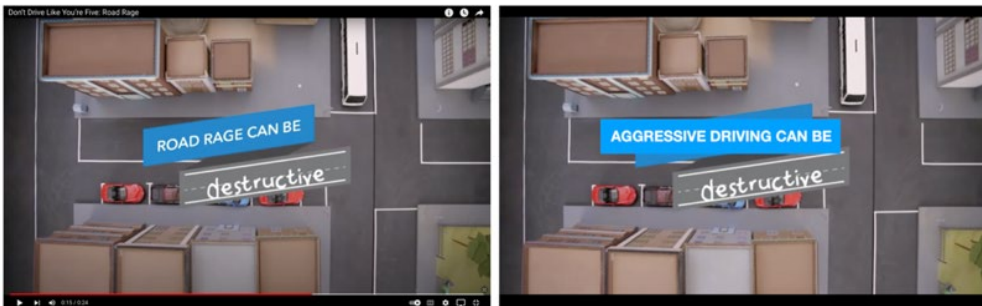
Figure B1. *Changes Made at 0:15 of the Original Advertisement*
Note. The left-hand side picture shows the original video, whereas the one on the right showcases the edited version that was used in this study.
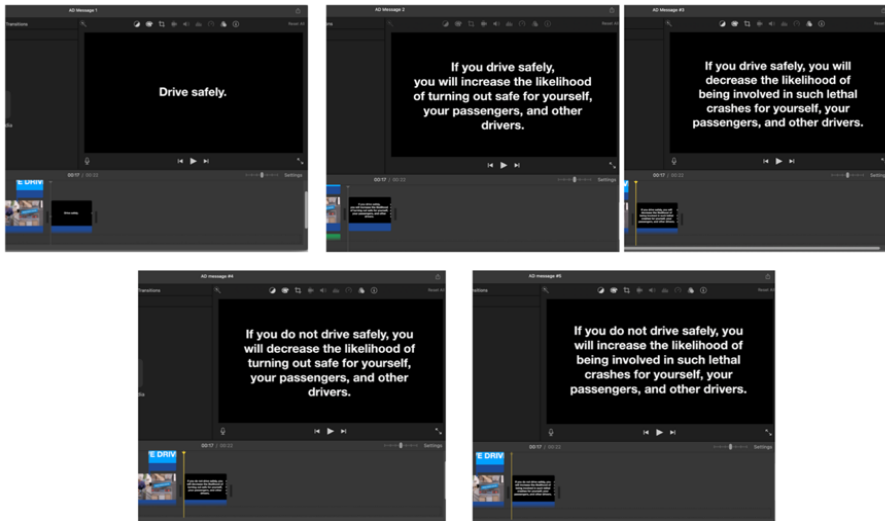
Figure B2. *Adding Messages to the Advertisements*
Note. Upper left: message 1. Upper middle: message 2. Upper right: Message 3. Bottom left: message 4. Bottom right: message 5.

Appendix C: URLs of the Advertisements

Advertisement with Message 1: https://youtu.be/DRriRvZ80N0
Advertisement with Message 2: https://youtu.be/Y3MYeKicyCE
Advertisement with Message 3: https://youtu.be/u-4gDTW9d2U
Advertisement with Message 4: https://youtu.be/Q_TbDNYIwRU
Advertisement with Message 5: https://youtu.be/Lo4Q0KD1s48

Appendix D: Revised Aggressive Driving Scale (rADS)

Key:
Unchanged: questions obtained straightly from ADS (Krahé & Fenske, 2002).
Partially Changed: questions taken from ADS and changed in two minor ways: (a) integrating repetitive questions form ADS to one single question or (b) adding more wordings to cover more of the aggressive driving behaviors listed by Tasca (2000).
New: brand new questions that were formed to cover the aggressive driving behaviors that were enumerated by Tasca (2000) but not included in the original ADS.

1. How often do you become angered by another driver and give chase with the intention of giving them a piece of your mind? (Unchanged)
2. How often do you become angered by a certain type of driver and indicate your hostility/annoyance by whatever means you can? (e.g., horn-honking, glaring, swearing, making rude gestures, getting into fights, flashing flashlights, braking in to stop the other driver…) (Partially Changed)
3. How often do you pull out of a junction so far that the driver with right of way has to stop and let you out? (Unchanged)
4. How often do you run red lights and/or stop signs? (Partially Changed)
5. How often do you weave in and out of traffic, regardless of the reason? (New)
6. How often do you drive so close to the car in front that it would be difficult to stop in an emergency? (Unchanged)

7. How often do you get angry at being overtaken and hence prevent other drivers from overtaking/passing you? (Partially Changed)
8. How often do you disregard the speed limit? (Partially Changed)
9. How often do you stop another car from pulling into your lane in front of you even when it is due to traffic conditions? (Partially Changed)
10. How often do you engage in improper passing another car? (New)
11. How often do you pass on the road shoulder or engage in improper lane changes (including failure to signal)? (New)

Appendix E: Anonymous and Non-Anonymous Aggressive Driving Behaviors

Anonymous aggressive driving behaviors (Q4) include:
● Tailgating;
● Weaving in and out of traffic;
● Cutting in too close in front of the vehicle being overtaken;
● Improper lane changes (failure to signal);
● Driving at speeds far in excess of the norm;
● Running stop signs or red lights;
● Horn-honking;
● Improper passing;
● Passing on the road shoulder;
● Failure to yield the right of way to other road users;
● Preventing other drivers from passing;
● Unwillingness to extend cooperation to motorists unable to merge or change lanes due to traffic conditions.

Non-anonymous aggressive driving behaviors include:
● Glaring at another driver to show disproval;
● Yelling or swearing;
● Obscene gesturing.

These behaviors were obtained from Tasca (2000).

Design of a Fine Motor Skill Training Smart Toy for Autism Spectrum Disorders

Chloe Gu

Author Background: Chloe Gu grew up in China and currently attends Shanghai High School International Division in Shanghai, China. Her Pioneer research concentration was in the field of engineering/computer science and titled "Foundations of Computing: A Hardware Perspective."

Abstract

Autism spectrum disorder (ASD) is a neurodevelopmental spectrum disorder that primarily affects social skills and language development. It has also been shown that both gross motor skill and fine motor skill development, even though delayed, can be crucial to an ASD child's social interaction. Yet the development of motor skills is often neglected by common therapeutic interventions, which focus more on social skill deficit. This paper aims to bridge this gap by proposing a design of a smart toy adapted for autistic children to practice their fine motor skills with little to no external guidance. The game is a reinvention of a traditional sliding block puzzle, 15-puzzle, where the player continuously slides pieces across a game board to achieve a specific configuration. The game is tailored to the needs of affordability, interactivity, structure, randomness, and stimulation that appeals to autistic children, using lights to create visual stimulus and the blocks to offer tactile stimulus. Through designing PCB boards and incorporating hall effect sensors as part of the design, a prototype is developed and implemented using Arduino, and is shown to exhibit stability and usability. The organization of circuitry is optimized to reduce the number of input pins required through using a RAM-like accessing method. The prototype is then evaluated qualitatively and quantitatively by the factors of affordability and potential for engagement, as well as its potential to be used to improve fine motor skills.

1. Introduction

Autism, also known as autism spectrum disorder (ASD), is a neurodevelopmental disorder that affects individuals throughout their lives. Since the effects can vary immensely from person to person, ASD is a spectrum disorder, ranging from low-functioning individuals to high-functioning individuals. Individuals with autism may have skill deficits in social interaction and social communication. They also often have restrictive and narrow interests (Frith et al.). Cognitive abilities among individuals with autism can also vary widely. Some individuals with autism often display exceptional abilities within specific domains, known as savant skills, while others may have learning difficulties (Heaton et al.).

ASD is commonly treated through a variety of approaches tailored to address the unique needs of individuals on the autism spectrum. Behavioral therapies, such as Applied Behavior Analysis (ABA), aim to modify behaviors, reduce challenging behaviors, and improve social skills (Cooper et al.). Speech and language therapy is demonstrated to improve social communication and language skills (Adams et al.). Occupational therapy addresses sensory processing and motor skill difficulties (Watling et al.).

Besides intervention therapies, toys, as an indispensable part of child play, can stimulate different cognitive processes, providing great educational value and fostering development across cognitive, language, social-emotional, and physical domains (Healey et al.) (Goldstein). They can also illustrate concepts well to children. For example, the concept of the mechanical advantage of gear systems can be illustrated using LEGO sets (Chambers et al.). In this context, toys are not only important in providing entertainment, but also serve purposes in cognitive and social development.

To further enhance the interactivity of toys, and in the advent of rapidly developing technology and virtual games, many toys have become equipped with "smart" features. These smart toys are new forms of toys that combine both tangible objects and electronic components to facilitate child-toy interactions (Cagiltay et al.). Like "non-smart" toys, these toys can be integrated into child education to improve cognitive abilities through augmented reality [10] or technology-based role-play (Kara et al.).

There is a need to adapt these toys for children with special needs. There are very few companies dedicated to the development of toys for ASD children (Canete et al.). Yet, there is evidence showing that when interacting with robots, children with ASD exhibit desirable social behaviors such as imitation that are otherwise rare (Ricks et al.). However, these methods exist almost solely within academia, and even when commercialized, are generally unaffordable due to their high prices.

This paper aims to formulate and prototype an affordable assistive technology or smart toy that can effectively capture the attention and preference of an autistic child, while also aiming to improve the child's fine motor skills through interacting with the toy. Recognizing the challenges associated with attention engagement in this population, the project focuses on developing a smart toy that is specifically adapted to the sensory and cognitive preferences of autistic children. By incorporating interactive features, dynamic visual stimuli, and personalized activities, the smart toy aims to provide a captivating and engaging play experience.

2. Background

2.1. Extrapolating the Demand

Motor skill delays can be observed from early infancy, and the disparity between individuals with ASD and typically developing individuals tends to widen over time. Even in the framework of 5 months, motor differences may already be noticeable. According to a study conducted on individuals at high risk of ASD that are 5-14 months old, motor delays were observed, with the majority exhibiting delays at 5-6 months (Wilson et al.). As infants progress into toddlerhood, the gap in motor abilities becomes more apparent, with autistic children showing delays in areas such as crawling, walking, and fine motor manipulation (Lloyd et al.). Similar results are shown using different tests of motor proficiency. In a study that conducted an

MABC-2 test (an evaluation on motor skills), the majority of ASD participants had significantly lower MABC percentiles in overall motor development, manual dexterity, ball skills, and static and dynamic balance than their typically developing counterparts (Liu et al.). This delay in motor development can impact various aspects of daily functioning, including self-care tasks, play skills, and, by extension, social engagement.

Furthermore, motor skills and communication are closely intertwined, with motor abilities playing a vital role in supporting communication development in children with ASD. Motor control and coordination are essential to produce sounds, gestures, and facial expressions involved in communication. Fine motor skills, such as finger movements for pointing or manipulating objects, contribute to expressive language development and symbol use. Motor skills show positive correlation to social skills, such as joint attention, turn-taking, and engagement in social interactions, which are fundamental to effective communication (Holloway et al.) (Iverson et al.). Therefore, addressing motor skill delays through early interventions can potentially have a significant impact on communication outcomes in children with ASD. While it is not clear whether social impairments are directly caused by motor skill deficiencies, interventions focusing on these skills may be beneficial to improve social interactions for individuals with ASD. Early intervention targeting motor skills sets the stage for improved communication and overall development in children with ASD.

2.2. Current Solutions

Traditional approaches feature human-guided interventions. In one case study on different preschoolers with ASD that underwent a human guided intervention, the participants showed improvements according to motor assessment tests before and after intervention. The intervention consists of biweekly exercise sessions adapted for preschool children (Duronjić et al.). Similar strategies regarding physical education are also used to help ASD children (Akin et al.). However promising the results, human guided intervention can be costly, and other tools can be used in complement with human-guided intervention to achieve a more well-rounded and effective intervention.

In addition to traditional motor skill intervention therapy programs such as occupational therapy, there are specific products designed to train motor skills for autistic individuals. Many of these integrate play into their design and are often designed as educational toys. These games and toys include sensory toys, smart toys, and virtual games based on sensors.

One game-based design seeks to bridge motor skill deficiency with a collaborative haptic-gripper (C-Hg) system designed to enhance fine motor skills in children with ASD. The system combines a commercial haptic device with a force sensing gripper. The design provides an individual training mode and a collaborative mode to practice both fine motor skills and social skills. User testing of the device conducted on both autistic and neurotypical children demonstrates the effectiveness of the C-Hg system in improving fine motor skills and increasing engagement among participants (Zhao et al.). The multi-skills based intervention is also utilized in a multi-functional smart toy design for ASD, as the user can switch between different modes easily to try a variety of games in different situations, indoors or outdoors (Canete et al.). While these multi-skills based interventions seem to show high motivation and promising results, it can be noted that the device itself is very costly due to its requirement of haptic sensors, and the games are not randomized enough

to sustain interest.

Another design features gesture games to examine the effects of learning on ASD individuals. The system features an interactive game of sorting and a leap-motion sensor used to detect the user's gesture during gameplay. The participant's performance in playing gesture games improved greatly, and the participants also showed signs of skill transfer. These results can only be interpreted in the scope of the study, as it is not possible to isolate the factors that contributed to the results (Cai et al.). Furthermore, similar problems arise in cost and the lack of randomization to sustain a child's interest.

Overall, current means of intervention for motor skills in individuals with ASD face common limitations. These studies have small sample sizes and are completed within relatively short periods of time, and the results can only be interpreted in the scope of the respective studies. Interpreted within the context of these studies, the lack of randomization or variety in intervention methods can hinder the sustained interest and motivation of individuals with ASD. Furthermore, the high costs associated with these intervention approaches often impede their commercialization and wide-scale use, limiting access for many individuals. Addressing these limitations and developing more robust and accessible intervention strategies is crucial to ensure effective motor skills training for individuals with ASD.

3. Proposed Approach

To address the demand for improving fine motor skills in individuals with ASD, there is a growing interest in developing products that offer independent practice and engagement without the need for constant human-guided interaction. When designing such products, it is essential to consider the importance of engagement and interest. Individuals with ASD often benefit from tangible reinforcement and interactions that make the experience more rewarding and enjoyable. Individuals with ASD tend to prefer simple, repetitive pursuits. However, to sustain interest, it is crucial to introduce randomization to prevent monotony and promote ongoing engagement (Garretson et al.). Products should be tangible, providing immediate stimulus and reward, and should incorporate elements that tap into the motivation of individuals, as motivation plays a significant role in sustaining attention during fine motor skill activities. By addressing these factors, products designed to improve fine motor skills can enhance the learning experience and promote the development of important motor abilities in individuals with ASD.

There is a need to develop a toy to practice fine motor skills for children. Summarizing and synthesizing the previous solutions, the proposed solution should have the following characteristics:
1. Affordable: cost-effective and reasonable for an average family
2. Interactive: should respond to the user's movements
3. Tactile and tangible: should consist of real objects to manipulate to practice fine motor skills and sustain attention
4. Structured: the game should be predictable and confined
5. Easy to understand and play
6. Immediate reward with stimulation: should have immediate feedback rewarding certain desired interactions between the user and the game.

To achieve the aforementioned characteristics, I propose a variation of the sliding puzzle, 15-puzzle. In this game, there would be 16 predefined slots to place a total of 15 colored blocks, then using the empty slot, the player needs to manipulate

the pieces by continuously sliding blocks into the empty slot to match colors in each row, making them the same for every row. The sliding block motion would consolidate and be a medium of practice for children with ASD. A valid configuration for the end state is shown below.
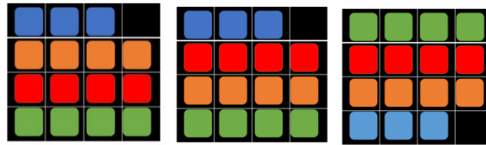
Figure 1. *Valid ending configurations for the puzzle.*

To incorporate sensory elements into the actual puzzle and reward potential "moves" that can contribute to a solution, the recognition of different pieces is required on the predefined gameboard. To reward moves that contribute to a solution, I aim to light up a single row every time the colors in the row are same (thus a partial solution). This would also make the game interactive and stimulating, thus fulfilling our predefined characteristics.

To create a prototype of the aforementioned game, Arduino, custom-made PCB boards, and 3D printing will be used to create a prototype of the game. Arduino, an open-source electronics platform, will enable the development of interactive and programmable components for the game, allowing for a customized and adaptable user experience. PCB boards tailor to specific requirements of the game, integrating electronic components and ensuring reliable and efficient operation of the game. Additionally, 3D printing will be used to fabricate tailored game components. This combination of technologies offers a flexible and cost-effective approach to prototype development, facilitating the creation of a tangible and engaging game that addresses fine motor skill challenges.

4. Design and Implementation

The design of the previously mentioned game involves two main components: the custom game board and the pieces that interact with the board. The game board is carefully designed with well-defined sections and features that facilitate the gameplay. To enable piece recognition, the game board incorporates sensors capable of detecting the differences between various pieces. This allows for interactive gameplay and provides immediate feedback to the player. Furthermore, the pieces themselves are constructed in a way that distinguishes them from one another both to the users and to the gameboard. Different types of pieces should have different colors or labels to differentiate.

For security and ethical concerns, microphones and cameras should not be used in the design.

4.1. Design 1

The design of the game incorporates a contact-based connection system, utilizing contact points on both the game board and the pieces themselves. The surface of the game board features strategically placed contact points that are connected to the

underlying circuitry and coated with a conductive material. These contact points allow for electrical connectivity when the pieces are placed on the board. Additionally, each piece is equipped with contact points on its bottom surface, enabling the activation of LEDs on the piece when placed on the corresponding contact points of the game board. By checking whether the circuitry is connected and by reading digital signals through an Arduino digital pin, differentiation of different conductive patterns can be achieved. Thus, each piece can be uniquely identified. This contact-based design enhances the engagement and interactivity of the game, while providing immediate visual feedback to the player through illuminated LEDs on the pieces.
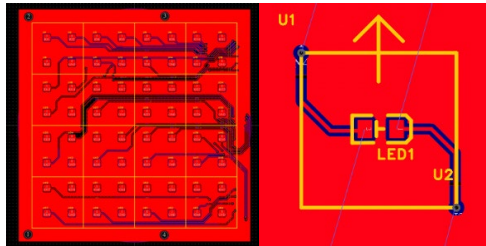
Figure 2. *PCB drawing of the game board and the piece.*
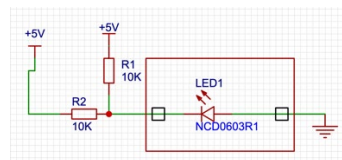
Figure 3. *Circuit design. The black square indicates the position of the contact points, and the dark red rectangle indicates the position of the module on the piece. R1 is a pull-up resistor.*

In the diagram shown above, by connecting a digital IO pin to the circuit, when the piece is attached, the digital IO pin would read a LOW signal, otherwise it would read a HIGH signal. In essence, by moving a piece into the circuitry, the LED is grounded. The pull-up resistor is used to stabilize the signals of the IO pin. By placing the "contact point" at different locations, we can identify the type of piece placed on top of the desired location. There would be one IO pin connected to each of these circuitries, with a total of 48 of such circuitries.
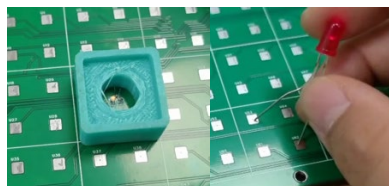
Figure 4. *Printed PCB board with no control over the LEDs.*

Since the LED is directly grounded, there would be no control over lighting the LEDs, as current passes through the LED the moment it is placed on the contact points, as indicated in Fig 4.

By modifying the circuitry and replacing the LED to be a programmable one, it is possible to sustain control over the LEDs. However, a significant limitation lies in the instability of a contact-based method. Based on testing and evaluation, it has been found that the method of contact points in the game design can be unstable and unreliable. This is due to the requirement for exact alignment between the contacts on the board and the corresponding contacts on the game pieces. Even slight variations in positioning can result in interrupted connections or inconsistent functioning of the game. As a result, a non-contact-based method is preferred for enhanced reliability and ease of use.

4.2. Design 2

Magnetic field sensing using Hall effect sensors offers an alternative for the differentiation of different pieces. Through placing magnets on the bottom of the pieces and using Hall effect sensors to detect the strength of the field and the proximity of the magnets, differentiation of pieces can be achieved. Compared to Design 1, the use of Hall effect sensors provides a cost-effective and stable method. Unlike color recognition systems that can be affected by lighting conditions or contact point methods that require precise alignment, Hall sensors offer a robust and efficient approach that is not easily influenced by external factors.

The Hall effect sensors are direct applications of the Hall effect, discovered by Edwin Hall in 1879. The Hall effect refers to the phenomenon observed when a current-carrying conductor is placed in a magnetic field perpendicular to the direction of the current. As a result, an electric potential difference, known as the Hall voltage, is developed across the conductor. This voltage is perpendicular to both the current flow and the applied magnetic field, as indicated in Fig 5.
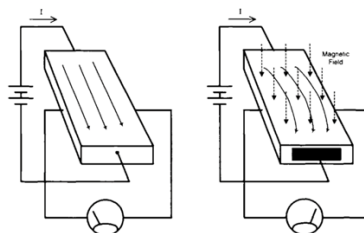
Figure 5. *Demonstration of Hall effect in a conductor (Ramsden).*

In the case of a closed circuit where current flows in a conductor, an external magnetic field would exert a Lorentz force on the electrons in the conductor, inducing charge separation and therefore a potential difference. In essence, the Hall voltage V_H is directly proportional to the drift velocity of the electrons v_d, the width of the conductor d, and the magnetic field B in the following equation:

$$V_H = v_d dB$$

Because the voltage across the conductor is directly proportional to the

magnetic field applied on it, it becomes possible to measure the relative strength of magnetic field. A typical application is using Hall effect sensors.

Hall sensors typically consist of a thin strip of semiconductor material, such as gallium arsenide or silicon. The strip is typically doped to control its electrical properties. Then the voltage signals are amplified using an amplifier, which is typically connected to the output pin of the sensor. When a magnetic field is applied perpendicular to the strip, the resulting Hall voltage can be measured by the electrodes attached to the strip, then amplified by the amplifier. The Hall voltage provides information about the magnetic field strength and direction, allowing for the detection of the direction and strength of the electric field.
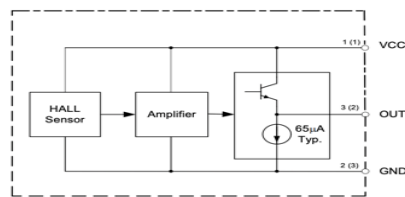
Figure 6. *A block schematic diagram for a Hall effect sensor (Diodes Incorporated).*
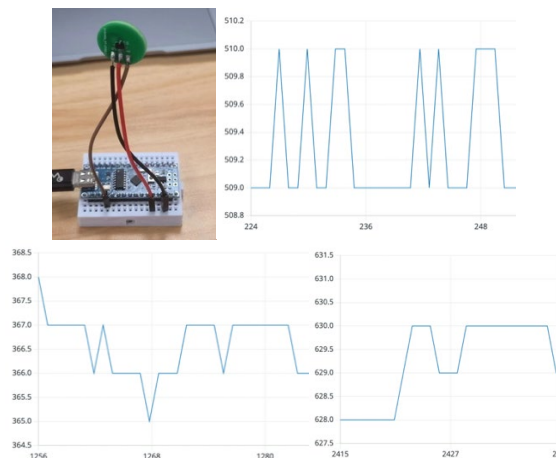
Figure 7. *The Arduino connections of the test. The plots are the readings of the analog pin against time.*

To implement the game board itself, I replicated this idea onto a total of 32 Hall effect sensors, connecting them in parallel. However, the large number of analog pins required for the design cannot be fitted into a single Arduino board.

Thus, an optimization is implemented. The optimization method is inspired by a similar process of accessing information in a RAM. After connecting every Hall effect sensor parallelly, we install MOSFETs in the circuitry as digital switches. We can control the MOSFETs using a digital pin on the Arduino, achieving the closing and the opening of the switch. Then by connecting the two ends of the switch, one with 5V and one with the positive terminals of the Hall effect sensors, we can activate

and deactivate Hall sensors. Fig 8 shows the schematic drawing of this optimization. By leaving three switches off and one switch on, we can "activate" a single row of sensors. Then by connecting an analog pin to each column, we can read the values of each Hall effect sensor. To incorporate sensory lights, I designed another PCB board for placing programmable lights, and controlling them with a digital pin.
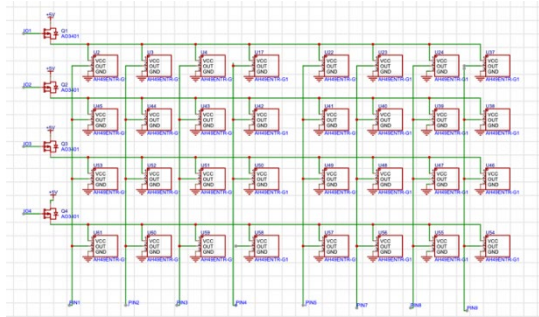
Figure 8. *Schematic drawing of the organization of MOSFETs, Hall sensors, and pin locations.*
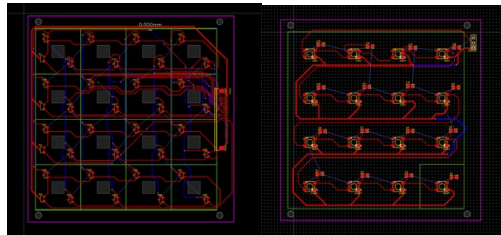
Figure 9. *PCB drawing of the game board (left) with the Hall effect sensors. PCB drawing of the LED board (right).*

After the design, a prototype was implemented and assembled. The pieces were equipped with magnets for detection and the pieces were tagged with a color label on the top-right corner to indicate both orientation and color. As indicated by Fig 10, the constructed prototype would light up when all pieces of the same color are placed within the same row. Even when they were not placed perfectly, the sensor was able to detect the placement of such pieces, which validates the usage of Hall effect sensors as a non-contact way of piece differentiation. This method allows tracking the state of the puzzle, which provides the opportunity of fully autonomous timer and tracker which determines the move count for the solve. The statistics would be displayed using an OLED display after each solve is completed.

Figure 10. *The prototype.*

The game is split into two stages. In Stage 1, the game starts with a generated random state, in which the player places the 15 pieces onto the board accordingly. A light signal is given when the correct piece is placed. After 15 pieces are correctly placed, the game enters stage 2. Then the player solves the puzzle, and a timer will start automatically when the player makes the first move. Then as the game is finished, the statistics will be displayed, and the game will continue after a few seconds.
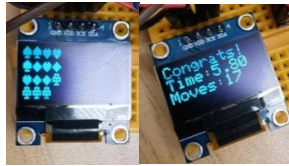
Figure 11. *OLED display.*

5. Results

Next, based on our guidelines proposed previously in the paper, we will evaluate the prototype.

Table 1. *Analysis of Toy.*

Affordability	The prototype consists of several magnets, 3D printed pieces, 3 custom made PCB boards, LEDs, MOSFETs, and Hall effect sensors, amounting to a cost of around $30, which can be further reduced with commercialization.
Interactivity/ Immediate reward	The puzzle interacts through light signals, signaling the completion of subsets of the puzzle, inducing interactions.
Tangible	The prototype is constructed, and the pieces can be picked up, placed, and slid across the game board.
Structured	The game offers a structured environment in a confined game board.
Easy to play	Regardless of whether the puzzle is solved, the child can interact with it by sliding pieces into the empty slot. The pieces can also be placed on the gameboard.
Stimulation	The puzzle interacts through light signals and the pieces, offering both tactile and visual stimulation.
Randomness	The game offers a total of $\frac{16!}{4!4!3!} = 252{,}252{,}000$ states to be solved in a total of 96 valid ending states (by permuting colors and leaving the blank), which provides randomness and creativity for problem-solving.

To learn about the game itself and analyze the complexity of the game, a Breadth First Search simulation is run to determine the longest number of moves to

solve the puzzle. The algorithm starts from the 96 solved configurations, then simulates one move at a time to reach a new configuration and marks the number of moves taken to get to the configuration. The distribution of the shortest move count to solve the puzzle is shown in Fig 12. The results show that the game offers 252,252,000 states, with a considerable number of states that require considerable numbers of steps to solve, which validates its randomness and complexity. A concern is the difficulty of the game. However, a solver could be implemented to guide the user towards a solution.
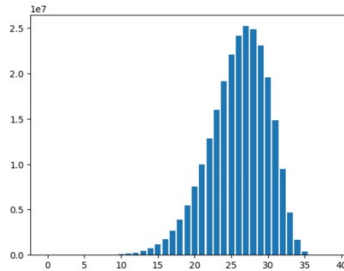
Figure 12. *Distribution of move count.*

A second experiment is conducted to validate the stability of the design and simulate stage 1 of the game by directly placing pieces on random spaces on the game board and checking whether the system detects the existence of the game piece. The experiment procedure is as follows:

1. Generate random position on the game board and the piece to be placed onto the game board.
2. Place the designated piece onto the game board directly, adjustments are not allowed.
3. Check whether the system responds (by lighting a LED).
4. Repeat steps 1-3 for 100 times.

The experiment was successful for 98 out of 100 times, and the remaining 2 times was able to trigger a response when slightly adjusting the placement of the pieces, which validates the stability of the use of Hall effect sensors as a way of detection of pieces.

6. Future Works and Conclusion

In terms of future works, although the designed game uses magnetic field sensing and Hall sensors demonstrate stability, there is a need for concrete evidence regarding user experience and engagement. Conducting extensive user testing with individuals with ASD is essential to get insight into the effectiveness of the game in terms of engagement and skill development over time. This would involve monitoring the level of engagement, measuring improvements in fine motor skills, and collecting feedback from users and their caregivers.

New games could be developed and implemented using the same or similar hardware components to enhance the versatility of the game and to implement multi-skill training. For example, a proposal could involve using the same pieces and board to practice color matching and further develop fine motor skills. By placing

the pieces onto the board in specific configurations based on color or pattern matching, individuals with ASD can engage in a more diverse range of activities that cater to their specific needs.

Improving the packaging of the game is also crucial. This includes making it more robust and integrated, ensuring that sensitive electronic components should be taken away from the sight of the users. Furthermore, packaging the game in an appealing and user-friendly manner can enhance its attractiveness and accessibility to individuals with ASD. By considering factors such as durability, ease of use, and visual appeal, the game can become a more desirable tool for fine motor skill development.

In conclusion, this paper proposes a design of a game board adapted for autistic children to practice their fine motor skills. The game is tailored to the needs of affordability, interactivity, structure, randomness, and stimulation that appeals to autistic children. Through designing PCB boards and incorporating Hall effect sensors as part of the design, a prototype is developed and is shown to exhibit stability and usability. The prototype is then evaluated qualitatively and quantitively through experiments, factors of affordability, and potential for engagement, as well as its potential to be used to improve fine motor skills.

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How Do Sociocultural Norms Lead to Gender Segregation and the Wage Gap in the Legal Profession?

Courtney Xia

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Abstract

This study aims to understand how sociocultural norms lead to gender segregation and the wage gap among lawyers in China. It is based on qualitative data from 9 interviews conducted with lawyers or former lawyers in Shanghai. Main themes identified from the interviews include past career choices, women's disadvantages in the workplace, work-life balance, and future career plans. It is found that gender segregation among Chinese lawyers is due to both external environments like gender-based preferences of the workplace and free choices based on internalization of gender roles. Both of these reflect sociocultural norms that assert women to be more domestic and less aggressive. These findings do not only reflect the gender dynamics in the law industry but can reveal the larger workplace environment in China and how gender norms continue to shape today's Chinese workplace.

1. Literature Review

Gender segregation in the workplace and the gender wage gap have been global issues that have gathered a lot of attention from scholars, economists, sociologists, and policymakers in the past few decades. Majority of existing literature prioritizes the West and the gender gap looks different in other sociocultural contexts. A series of journal articles are reviewed to examine these issues in both vertical and horizontal contexts, identify the internal and external factors behind the phenomena, and understand the issues' prevalence in the legal profession and in China.

1.1. Vertical Gender Segregation

In the 1960s in the United States, women only occupied one-third of the workforce and fifteen percent of managers (Hegewisch & Hartmann, 2014, p. 1-2). Following an increase in women's participation in the workforce due to World War II, a series of legislative acts such as the Equal Pay Act and the Equal Employment Opportunity Act were enacted to improve equal pay and fair labor practices (Langdon & Klomegah, 2013, p. 174).

However, women's median income is still only 76 percent those of men's, and women continue to occupy over 80 percent of the most common occupations for women

such as pre/kindergarten teachers, dental assistants, registered nurses, and librarians in the United States (Hegewisch & Matite, as cited in Hegewisch & Hartmann, 2014, p.1-4). Accompanying imbalanced gender compositions in many industries, Olsen and Walby (2004) found out that for every 10 percent rise in the percentage of males in an occupation, there is a corresponding 1.3 percent rise in the wage rate. Women and men's occupational segregation and the inverse relationship between women's proportion in the occupation and the average wage is referred to as vertical gender segregation.

Vertical segregation is reflected in the historic gender composition of the computer programming occupation. In the 1970s and 1980s when the computing industry was in its infant stage, women represented over one-third of the whole computing workforce (Hegewisch & Hartmann, 2014, p. 5). However, women's representation in the industry dropped to less than one-fourth of the computing workforce around 2007, when the industry became more developed and recognized (Hegewisch & Hartmann, 2014, p. 5).

There also persists a glass ceiling that poses barriers for highly educated and skilled women to enter the top of the labor market. Blau and Kahn (2017) found that the gender wage gap is more prevalent and decreases at a slower rate at the top of the labor market than at the middle or bottom, which aligns with research across eleven European countries that also discovered similar patterns (Blau & Kahn, 2017, p. 807). Despite the role of education in increasing wages, it raises men's wages higher than those of women's wages (Langdon & Klomegah, 2013, p. 196). Therefore, even though women's education level has exceeded those of men, gender segregation persists; women are almost two times more likely to be in lower-paying service occupations, while men are 10 times more likely than women to be in higher-paying technical professions (Langdon & Klomegah, 2013, p. 196).

1.2. Horizontal Gender Segregation

Not only is gender segregation prominent in splitting women and men into different professions vertically in the labor market, but women face segregation and wage differences from men even within the same profession.

In the healthcare industry, graduates of the same medical schools face huge differences in career potential with respect to gender. In Switzerland, Hay et al. (2019) found out in a longitudinal study that graduates of medical schools have distinct career paths with respect to their genders. Women face lower rates of employment, enroll in specializations with less prestige and remuneration, and have less career aspirations than their male counterparts (Hay et al., 2019).

Both the gender wage gap and segregation occurs even in female-dominated professions. Giapponi and McEvoy (2005-2006) found that in the female-dominated profession of social work, the median income for female social workers was $34,135 while their male counterparts earned $37,503. Snyder and Green (2008) also found that gender segregation is pervasive in nursing, a female-dominated profession, taking forms of disproportionate clusters in particular specialties based on perceptions of gender characteristics, whereas male nurses tend to work on specialties that are perceived to be more masculine.

1.3. Internal Factors Leading to Challenges Faced by Women in Career Paths

Due to the lifelong socialization process, women's internalization of gender roles can drive them to make gender-based occupational choices, which hinder their career development and lead to gender segregation in occupations and industries (Langdon & Klomegah, 2013).

Firstly, traditional gender ideology likely leads women to choose jobs that are

perceived as feminine but have lower wages. Barbulescu et al. (2012) found that women who graduated from MBA programs tend to only apply for jobs such as management instead of finance and consulting because they perceive higher levels of success and identify with these jobs that are seen as feminine more often. Avoidance of the perceived masculine jobs that offer high remuneration and prestige can result in gender segregation since women end up in less rewarding jobs (Barbulescu & Bidwell, 2012, p. 737).

In addition, institutionalized notions of gender norms lead women to understand their roles in highly gendered terms, including the expectation for women to achieve a balance between work and family due to the traditional division of labor (Charles, 2003, p. 282). Bender (2005) found that women tend to be more satisfied in their jobs than men because they value flexibility in jobs and choose jobs that can provide them with flexibility. Similarly, Hay et al. (2019) found that among graduates from medical schools in Switzerland, women are more likely than men to consider part-time jobs. This occupational choice, as will be explored in the next section, can greatly impact gender segregation and the wage gap. Women's tendency to enroll in jobs that offer flexibility and are perceived as being feminine can lead to wage gaps and gender segregation in occupations and industries. Blau and Kahn (2017) found that this factor is quantitatively the most important measurable factor contributing to the gender wage gap.

Beyond occupational preferences, another way gender-based choices can impact women's career manifests in wage negotiation. Babcock and Laschever (2003) found that many women do not negotiate salary as well as men. Bowles et al. (2007) found that the reason why such a phenomenon occurs is because female job candidates are more likely to be penalized than their male counterparts for initiating negotiations for higher compensation. Lower base pay during initial hiring can perpetuate the wage disparities as women progress through their careers, according to Giapponi and McEvoy (2005-2006).

1.4. External Factors Leading to Challenges Faced by Women in Career Paths

Even though practices such as shorter working hours and part-time jobs are favorable to help women achieve a more flexible and balanced lifestyle, they are penalized by the workplace. Cortes and Pan (2016) found that highly skilled jobs increasingly reward workers for overworking long hours. Women's unwillingness to forfeit flexible working hours results in occupations that greatly reward overwork to have the largest gender gap in earnings (Cortes & Pan, 2016, 22). It therefore explains why the gender wage gap permeates at the top of the wage distribution. Similarly, when women work part-time or spend less time working full-time to care for their families, their wages are lower relative to men who spend less time doing so (Olsen & Walby, 2004).

Furthermore, discrimination and preferences of the labor market also pose challenges for women in the workplace. These two factors account for 38 percent of the gender wage gap, according to Olsen and Walby (2004).

Firstly, the motherhood penalty for women and the fatherhood premium for men continue to permeate the workplace (Blau & Kahn, 2017, p. 854). Hay et al. (2019) found that motherhood increases all negative impacts that gender has on career development.

Statistical discrimination also plays a very important role in how women, especially mothers, can be disadvantaged in the hiring process. When employers perceive differences in productivity and stability between mothers and nonmothers or between women and men, they tend to favor one group over the other in the hiring and training processes (Blau & Kahn, 2017, p. 818).

1.5. Gender and the Legal Profession

Gender segregation and the wage gap penetrate the legal profession just as in many other industries.

The wage gap can be substantiated by men reporting an average income of $86,756 and women $44,210 among Toronto lawyers in 1985 (Hagan, 1990, p. 838). The same study also found that men can translate fine education, specialization status, and mobility ladders in firms into more income than women (Hagan, 1990, p. 849).

The glass ceiling preventing women from reaching high positions is also found in the legal profession. A substantial gender disparity in rates of being promoted to partnership positions showcases how gender is segregated at the top of the wage distribution (Dinovitzer et al., 2009, p. 63). In large companies, it is found that the rate at which women attain equity partnership is less than half that of men (Dinovitzer et al., 2009, p. 63).

The factors of the wage gap and segregation in the legal profession are also similar to those in the general labor force, as explored in a longitudinal study of Canadian lawyers' departure conducted by Kay et al. (2013). Factors like women's family responsibilities played an important role in women's departures, since fertility breaks and gaps between work and caring for children take the greatest toll on women's careers (Kay et al., 2013, p. 1255). Female lawyers' preference for flexible jobs remains the same in law as in other industries since lawyers who have flexible full-time schedules depart 20 percent slower than those without flexible schedules (Kay et al., 2013, p. 1248). Discrimination also continues to play a role in women's departure, as experiences of discrimination increase women's rate of leaving private law 29 percent more quickly than those who have not experienced gender-based discrimination (Kay et al., 2013). John Hagan (1990) also concluded that discrimination results in 29 percent of the wage gap among Toronto lawyers.

1.6. Gender and Work in China

As the gender wage gap and gender segregation are prevailing issues in the global setting, China's workplace is not free from its invasion. However, the unique political and social atmosphere of China adds a unique layer to the issue.

Historically, Chinese society had very rigid gender roles under the teaching of the historical Chinese scholar Confucius. Women were socialized to stay at home as subordinates of men and were only recognized as being wives, mothers, etc. Prior to 1949, women only made up 7.5 percent of the workforce, according to Bulger (2000, as cited in Burnett, 2010).

After the Chinese Communist Party formed the People's Republic of China, Mao Zedong started reforming the economy (Burnett, 2010, p. 293). Furthermore, with the goal of achieving economic growth and dealing with labor shortages, he started encouraging women's participation in the labor force (Burnett, 2010, p. 293). Even though there were still gender disparities in terms of promotion, industries to work in, and the type of work performed, women received equal pay for the same work and began taking leadership roles that were traditionally held by men (Burnett, 2010, p. 294). These reforms led to a boost in the high female employment rate in China, which remains even now (Qian & Li, 2020, p. 42).

However, this political campaign only focuses on including women in the public sphere, but it never seeks to interfere with issues in family settings. In the private sphere, traditional ideology is continued, if not being increasingly supported (Qian & Li, 2020, p. 42). Gender equality in family settings is a lot less present than those in public sectors (Qian & Li, 2020, p. 42).

Currently, despite the law establishing equality between men and women and women receiving equal education as men, social norms still result in gender-based

segregation and wage gaps. Women make up approximately forty five percent of the country's workforce, but a working woman's salary is seventy four percent less than that of a man's wage on average (China's National Bureau of Statistics, 2004, as cited in Burnett, 2010). Women also tend to be underrepresented in leadership or other high-ranking positions.

In summary, a lot of prior scholar work examined the social phenomenon of gender segregation and the wage gap. Most of the works focused on the United States and Europe, while gender issues in work can look different in other contexts. While there is literature about gender segregation and the wage gap in Chinese society and the law profession, little is known about Chinese lawyers and their specific experiences. Therefore, this study aims to understand the effect of gender on past career choices, disadvantages faced in the workplace, work-life balance, and future career paths in China's legal profession.

2. Methodology

The paper is based on qualitative content analysis based on nine interviews; seven with female lawyers or female former lawyers, and two with male lawyers. All interviewees were non-litigation lawyers who specialize mainly in international trading and business, except for one male litigation attorney who works in criminal law. The current positions of the interviewees include former associates, associates, and partners. All interviewees come from the same law firm in Shanghai, China, and the interviews were therefore conducted in Mandarin and later translated into English.

I mainly followed a chronological order to understand lawyers' experiences in the workplace. I started off talking about when lawyers first entered the workplace, covering topics of the hiring process and choice in specializations. I then moved on to the current conditions of lawyers, discussing work-life balance and experiences working as a lawyer. Lastly, I discussed future plans and ambition.

Throughout the interviews, I consistently posed follow-up questions to understand interviewees' experiences with regard to gender and workplace.

After all interviews were collected and translated, I first examined the interviewees' responses to understand the overall work environment and culture of Chinese lawyers. For example, interviewees' responses regarding difficulties faced in the workplace and whether the work environment is supportive of fertility breaks can help me piece together the overall picture of the workplace and its gender relations. In addition, I examined individuals' responses to more personal questions, such as their decision-making processes and their career paths. These responses provided me with diverse points of view, which helped me to identify variations among individuals and the role of free choices and personalities in gender segregation. Therefore, my analysis of both general patterns and individual thoughts and choices formed my study of gender in gender segregation among Chinese lawyers. Lastly, I identified four main topics that are prevalent in interviewees' responses: choice of specialization, challenges faced by women in the workplace, work-life balance, and future plans.

3. Methodology

3.1. Choice of Specialization in China

Interviewees gave a variety of responses in terms of what causes them to become a corporate lawyer or a litigation attorney. Given that corporate lawyers work on legal documents and do not go to court and litigation attorneys do, some of the responses

about the choice of specializations exemplify slightly gendered characteristics. The only litigation attorney in my interview stated:

> "In the litigation business, you can directly feel the confrontational nature of being a lawyer. It's an interesting process to work on... There's a lot of sense of fulfillment in being on appeal."

According to the experience of this litigation attorney, his job is associated with confrontation and fulfillment, which aligns with his personal interests and prompts him to stay as a litigation attorney. However, the same characteristic that interests this man is not as intriguing for women. On the contrary, it can become a restricting force that diverted women away from becoming litigation attorneys. One female associate stated that she did not choose to be a litigation attorney due to the confrontational nature of the job:

> "Litigation requires you to go to court, which is a more aggressive activity. If it is not a lawsuit, it will not be so direct and confrontational. So I made a choice between litigation and non-litigation."

A similar response is found in another non-litigation associate:

> "Because my personality is not suitable for public speaking and debating, I first chose non-litigation."

One lawyer also provided an observation that can be generalized to the overall litigation versus non-litigation specialization:

> "Looking at the entire litigation and non-litigation environment, there are still more male litigation lawyers. If you look at non-litigation, there are more women. In fact, in terms of resilience in transactions and carefulness in reading documents, girls have a greater advantage. Men may like direct impact."

Despite this lawyer attributing advantages for men and women, these characteristics are highly gendered, suggesting the internalization of gender stereotypes. These responses show that women might avoid typically masculine specializations of litigation and choose more feminine specializations of corporate lawyers instead. Therefore, institutionalized gender roles lead to segregation in the legal profession as men and women cluster toward different specializations based on their gender. This can also potentially lead to the gender wage gap.

In addition to gender-based characteristics, agency, the power to make choices, is distinctive in men's and women's descriptions of why they became corporate lawyers. The various factors that drive them to become corporate lawyers include the lack of interpersonal connections with clients that litigation attorneys need, internship opportunities as a corporate lawyer that happen to be available, and incompatibility between characteristics of litigation attorney and personalities, as mentioned in the previous paragraph. While these explanations generally reflect a lack of agency in that the external forces compel them into their final decisions, the male interviewee's response suggests the opposite:

> "In general, after working for a period of time, I feel that my interest lies in non-litigation transactions."

Agency is shown in this response, as this lawyer reasons that becoming a litigation attorney is driven by his personal preference and a conscious choice. Therefore, despite that these answers are not explicitly gendered, they reflect implicit gender roles and expression, where men present themselves with more power to make conscious, independent choices, whereas women tend to attribute their decision-making process to be influenced by external factors instead of preferences.

In addition, it is also found that the specializations that require frequent business trips are favored by men. Initial public offering lawyers, for example, are expected to go on regular business trips, sometimes exceeding 300 days per year for junior IPO lawyers according to a female associate. Furthermore, the associate also mentions that businesses may lay in remote locations or near factories where lawyers have to reside alone in these areas, so their work becomes associated with physical labor and safety concerns. This leads to human resources favoring male over female IPO lawyers based on statistical discrimination and female lawyers avoiding this specialization. Therefore, as both the demand side and the supply side show a gendered preference for the IPO specialization, gender segregation of specializations within the law profession can be found. Sociocultural norms therefore drive women to specializations that are safer and more domestic, leading to gender segregation and potential wage gaps.

3.2. Disadvantages Faced by Women in Work

Interviewees gave varying responses to whether women face disadvantages in comparison to their male counterparts in the work environment, and such variations correlate with their levels in the law firm, whereas junior associates tend to express less gender inequality than senior associates or partner lawyers.

For example, when asked whether the hiring process prefers men over women, the few junior associates all expressed that they did not experience gender differences in the hiring process. However, more senior or partner lawyers mentioned both experiencing women's disadvantages as a job applicant or taking gender into a factor of consideration when hiring new associates or interns. This is due to employers' expectations that women are likely to form families and bear children, therefore having the potential to disturb patterns of their professional life and the team. Furthermore, similar to the case of IPO lawyers, employers expect males to be more flexible in terms of going on business trips than women because they have fewer safety concerns. One example stands out in that in previous experiences applying for jobs, a female candidate passed their selections for many rounds but was then informed verbally that they wanted a male. With no concrete evidence to report such practices, the interviewee had to suppress her anger since her time was wasted and move on. Therefore, statistical discrimination exists due to employers' perceptions of how women might be less stable and productive than men, and can post barriers for women in the hiring process.

The reason behind the different perspectives between senior and junior associates has two potential explanations. Firstly, junior associates are all in their twenties in this study, while senior lawyers or partners are typically older. As time progresses, gender inequality has likely reduced, so junior associates who entered workplaces later than their older counterparts might not have experienced the same level of gender inequalities as their older counterparts.

Secondly, lawyers of higher ranks, such as senior associates or partners typically are exposed to, or at least have opportunities to engage in, occasions of socializing with clients, where women face more disadvantages than in the hiring process. In these informal socializing occasions that are out of the job descriptions of lawyers, personal connections and trust are built between clients and lawyers, which has a significant impact on the success of lawyers.

Among the lawyers that face such situations, female lawyers established that most occasions where such socializing events take place are more appealing and inclusive to men than they are to women. Whether at dinner tables or in karaoke places, alcohol is highly involved, which female lawyers tend to avoid due to safety concerns. One female partner mentioned:

> "You want to sing karaoke after dinner, and maybe get a massage together. These things happen from time to time, but I definitely can't do this. I rarely eat with clients, and when I do, I don't even touch the wine glass. I know that I will lose some business opportunities because of this, but I accept this matter calmly because it is the consequence of my choice."

This lawyer avoids socializing occasions with clients with acceptance of potential losses. Another female partner mentioned that others can determine that she must have exceptional expertise because, without which, it would have been impossible for her to have reached where she is since she does not drink with clients. Both socializing events preferring men to women and choices made by women to avoid such occasions lead to women losing potential opportunities in work, leading to gender wage gaps. However, many respondents acknowledged that such disadvantages are not unique to the legal profession but are prevalent in the overall workplace in China.

Nevertheless, despite the hiring process and socializing occasions both showing potential imbalances that favor men over women, the promotional opportunities, according to the interviewees, are based purely on lawyers' abilities to perform well in their jobs, while gender considerations have no direct impacts.

3.3. Work-life Balance and Parenthood

In terms of flexibility, both men and women reached the consensus that the workload of lawyers is heavy, despite the financial rewards being proportional.

Due to the intense workload, the working culture for lawyers is generally not supportive of maternity leaves. According to the interviewees, law firm policy does not have power over such fields, but the specific teams and associates' bosses have more power over their employees. Therefore, the support or penalties that individuals receive for maternity leaves vary case by case. For example, some partners might support their associates in taking maternity leaves and even let them rest for more than the legally required time in China. In China, women's legal maternity leave is 14 weeks, while men's legal paternity leave is only 15 days (Lvtu editors, 2023). Their colleagues will cover the additional work due to their absences during the months of fertility breaks. On the other hand, some partners might require their associates to leave their jobs permanently if they are unavailable for a few months. This is because one associate's absence for a few months can be costly for the team while the other colleagues are occupied with their own work. In this case, hiring an additional employee might also be unrealistic and inconvenient. Therefore, female lawyers face difficulties finding balance between work and family when they intend to bear children.

3.4. Future Career and Family Plans

Career plans vary for female interviewees. For both men and women who are dedicated to continuing their careers as corporate lawyers, they anticipate the heavy workload and nature of the profession. However, women also consider other career options that allow for a better focus on family. For example, one female interviewee stated that when she reaches the age to form a family in the future, she will leave her current profession. She plans on becoming an in-house lawyer, employed by a single firm, which offers a predictable and stable working schedule:

> "If I have plans to start a family in the future, I will change careers. The current intensity and time of work is quite contradictory to starting a family."

She mentioned that she values a personal life more than financial rewards. Another female lawyer also stated that she might consider becoming an in-house lawyer in a few years, even though she currently does not have plans related to forming a family. A former lawyer who left her job to work in her family business reasoned that this decision diminished her potential in her personal career life but is beneficial to her family and her children's education which she also values a lot:

> "After forming a family, I tried to find the maximum value of the family sum, not the maximum value of myself."

Working for their family business allows her to maintain a career life where her past experiences are still utilized. Therefore, it is a voluntary and satisfactory decision where she maximized her family's utility and did not sacrifice much of her own. The two male lawyers, on the contrary, both stated that they were determined to stay in their current positions. While one does not yet have plans about forming a family and believes that he will be able to sustain both work and family in his current job, the other one stated that bearing children and the potential economic pressures associated with it will lead him to work harder and seek to support his family financially better:

> "I want to give my children better living conditions and education. Therefore, I will have increased financial pressure, and I hope to better support my family through work."

Thus, a gendered difference is shown as women consider leaving their jobs to better accommodate the needs of the family, while men tend to stick with their current jobs. This reflects traditional divisions of labor in households, where women tend to choose more flexible jobs to accommodate the needs of their families. Since flexibility is penalized in highly skilled occupations, such occupational choices can lead to gender wage gaps and segregation.

It is also found that many women do not tend to explicitly state that they are ambitious while men do. One female junior associate stated:

> "I'm not that career-oriented girl, I want to be more balanced with my life."

Even women who made it to the partner positions did not explicitly state that she is ambitious:

> "In fact, many people think that I am ambitious, but I don't think I am very ambitious. Externally I give people a strong impression, but internally I feel like a very lazy person."

On the contrary, men explicitly stated that they are ambitious:

> "I hope to make some achievements. On the one hand, it is to make money, on the other hand, it is recognition of one's own work ability."

These gender differences in expression of ambition align with previous studies that found women more accepting and less ambitious than men. This reflects internalization of cultural norms which can potentially lead to gender segregation and wage gaps.

4. Conclusion

Overall, even though outright discrimination seems limited in the legal profession in China, sociocultural norms lead to gender segregation and females facing multiple disadvantages in work. Traditional Chinese gender norms that women should be more domestic are reflected in women's lesser involvement in socializing occasions and specializations that require frequent business trips, based on both women's internal choices and the environment's preferences for men. The traditional division of labor in households where women should care for their families is also mirrored. In the hiring process, statistical discrimination can disadvantage women due to employers perceiving women to be less stable or productive due to their responsibilities in households. Internalization of such social expectations results in some women considering switching to occupations that offer flexibility and stable working hours so they can better support their families. Lastly, gender-based differences in power of agency and description of ambition, along with split in masculine versus feminine jobs, show institutionalized traditional gender ideologies, as women tend to show lower levels of agency, aggression, and ambition. Overall, gender segregation and the wage gap in the legal profession are due to both individual workers internalizing gender roles and external environments showing preferences based on these sociocultural norms.

Some limitations of the paper include, firstly, that all interviewees are attorneys from the same firm from the same city, Shanghai. This can potentially result in homogenous answers that represent the culture of the firm, making the findings of the study ungeneralizable to the wider social context. However, the attorneys showed a variety of opinions as they have different levels, work in unique specializations, and come from distinctive teams. Furthermore, many attorneys mentioned that the different gender treatments they experience are not limited to the law industry, not to mention the single firm, but is a common trend that can be found in many other industries in the Chinese workplace. Therefore, even though all interviewees come from the same firm, their unique stories and perspectives are adequate to reveal a more generic picture of gender and the law profession in China. Furthermore, a total of two males in comparison to seven females included in the study can potentially lead to an unbalanced representation of the two sexes, making the results skewed. However, the main purpose of this study is to understand how women's choices, challenges, and future plans regarding work are influenced by gender norms. The inclusion of the two males into the study is to provide an opposite perspective that allows for comparison. Therefore, even though females make up the majority of interviewees, the interview data are sufficient to conclude how gender affects women's career paths in China. Future studies, however, can include interviewees from more diverse backgrounds with a more balanced gender ratio to allow for a more accurate understanding of the workplace and gender in China.

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A Qualitative Comparison of the Fast Fourier Transform and the Morlet Wavelet Transform for Potential Depression Diagnosis Using Resting-State Electroencephalographic Data

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Abstract

The diagnosis of Major Depressive Disorder (i.e., "depression") has long relied on subjective measures, such as patient self-evaluation and doctor analysis. With few quantitative factors, this leaves depressed patients liable to be misdiagnosed and to not receive the necessary help to improve their condition, should they require it. To improve a depression diagnosis, more quantitative methods must be explored. One such method is the analysis of electroencephalographic (EEG) data, which has a long history of usage in large-scale neurological assessment and, when taken from a resting-state patient, has potential applications in clinical settings. However, there are many different signal processing methods that can be used to extract features from EEG data. Thus, it is important to choose the most accurate method for depression-specific features. In this paper, two signal processing methods, the Fourier transform (FT) and the continuous wavelet transform (CWT), are used to analyze actual continuous, resting-state EEG data at well-established frequency bands to create similar topographic maps of a subject's brain. The transforms and topographic maps are created using the most recently updated MATLAB software as of September 9th, 2023, the 2023.0 version of the EEGLAB software, and the most recently updated FieldTrip toolbox software as of August 17th, 2023. The transforms' respective topographic maps are then assessed qualitatively to detect depression-specific outputs to determine the strengths of each transform in potential quantitative depression-diagnosis.

1. Introduction

1.1. Depression

Mental health levels have been rapidly falling around the world, especially among American teens. Specifically, about 3.8% of the world's population experiences some form of depression, and about 9.7% of U.S. youth experience severe Major Depressive Disorder (MDD) ("Depressive disorder (depression)", 2023; "The State of Mental Health in America", n.d.). In this paper, the more colloquial term "depression" is used interchangeably with the medical name of MDD. However, most modern depression diagnosis strategies, such as psychiatric evaluation by the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5) criteria, rely on honest patient input and the doctor's analysis of the patient's perceived symptoms (*DSM-5 fact sheets*, n.d.; "Depression (major depressive disorder)", 2022). This system relies on little quantifiable data, leaving patients liable to be misdiagnosed or to have their mental health issues overlooked. Thus, depression diagnosis can be improved by examining what physical, measurable quantities correlate with depression, so that one can examine data objectively to ultimately create a fairer method of depression diagnosis based on the individual. After the physical symptom one would like to analyze is determined, it is important that one chooses the optimal method of analysis to give one the most accurate idea of the potential of the chosen diagnosis method. This paper assesses the effectiveness of two different signal processing methods, the Fourier transform and the wavelet transform, by examining electroencephalographic (EEG) data and considering the different factors that lend themselves to effective depression-focused EEG data analysis.

Electroencephalography (EEG) is a non-invasive method of recording an electrogram of spontaneous electrical activity in the brain. When collecting EEG data, electrodes are placed along the scalp as shown in Fig. 1. In EEG data analysis there are typically three different stages necessary. The first is preprocessing, which includes signal collection, removal of artifacts, and other steps to make the data suitable for analysis. The second stage is feature extraction, where a feature is the characteristic measurement, transform, or structural component that is being examined. The third and final stage is signal classification which can be solved by linear analysis, nonlinear analysis, and other mathematical and computational methods (Al-Fahoum et al., 2014). This paper focuses on the feature extraction step of the process.

In depression diagnosis, EEG has been shown to differentiate patients with and without depression at a group-level, but its diagnostic potential on an individual level has yet to be realized. However, because quantitative EEGs produce complex data sets at multiple frequency bands, depending on electrode location and patient vigilance state (eyes open vs. closed), and because of its already established effectiveness on a group-level, the author believes EEG data analysis will be vital to depression diagnosis in the future (Mohammadi et al., 2015). In fact, the short-time Fourier transform, a variation of a technique discussed in this paper, has already been used to analyze EEG data and determine a correlation between speech data and depression (Elfaki et al., 2021).
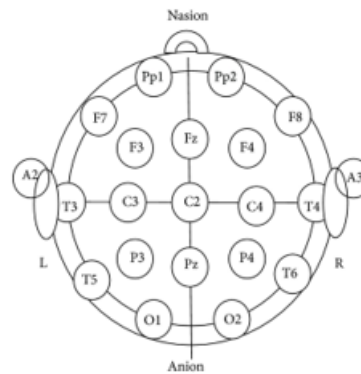
Figure 1: *Standardized electrode placement scheme, with each electrode labeled in a letter-number combination (Al-Fahoum et al., 2014)*

1.2. Fourier and Wavelet Signal Transforms

This section describes the two signal-processing techniques discussed in this paper. The first method, the discrete Fourier transform (FT), is a transform that converts a function into a form that describes the frequencies present in the original function (typically from a graph with time on the horizontal axis against frequency on the horizontal axis) by decomposing the original function into a sum of sine and cosine waves. See Fig. 2 for an example. The inverse discrete Fourier transform (IFT) likewise converts from a frequency domain to a time domain. The fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) are methods for computing the discrete Fourier transform and its inverse efficiently (James, 2011).
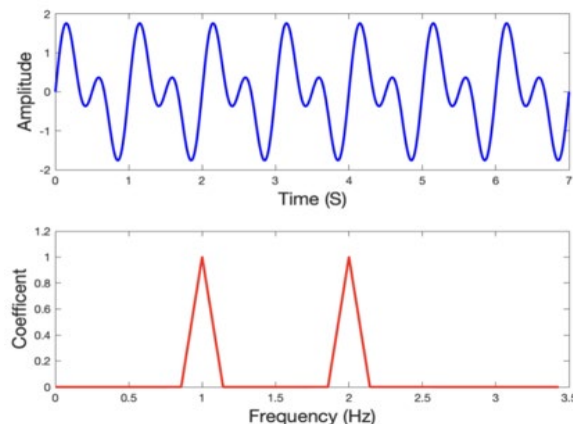
Figure 2: *Top: a time series signal. Bottom: the signal transformed to Fourier (frequency) space. (Talebi, 2022)*

The second method used is the wavelet transform. A wavelet is a simple short-term oscillation with two important properties: scale and location. Scale is how stretched the wavelet is, and it is correlated to frequency in Fourier transforms (see Fig. 3). Location is the location of the wavelet in time, since unlike waves, wavelets are only non-zero for a brief moment (see Fig. 4). The wavelet transform is used to compute how much of a wavelet is in the signal function for a particular scale and location by convolving it over the function.
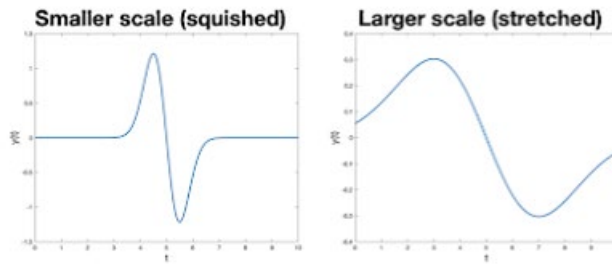
Figure 3: *scale of Wavelet transform (Talebi, 2022)*
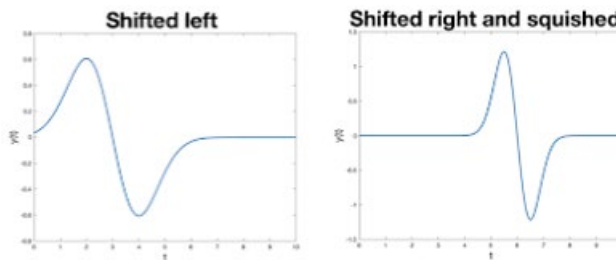
Figure 4: *location of Wavelet transform (Talebi, 2022)*

To understand the difference between Fourier transforms and wavelet transforms, it is important to understand the Heisenberg Uncertainty Principle, which says that the degree of frequency spread and temporal spread cannot both be very small. In other words, if one wants to know the frequency of a signal to some significant degree of uncertainty, then at some point one cannot know the time at which the frequency occurs. The two transforms differ primarily in that with Fourier transforms, functions that are localized in the time domain have transforms that are spread out across the frequency domain and vice versa, so one knows either the frequency of or time at which a signal occurred perfectly, and the other property not at all. With wavelet transforms, however, the opposite case is true — that is, one can say the initial function had some particular amplitude variation that occurred during some identifiable times.

This is the main difference between Fourier transforms and wavelet transforms, and it lends itself to interesting discussions when considering EEG data. There are other more technical differences as well, which are described in Section 4.

The wavelet transform is often preferred over the pure Fourier transform due to its ability to capture time-varying frequency content and has historically been used in event-based EEG data analysis. However, resting-state EEG data for depression diagnosis

should not vary significantly over the data collection period, given the absence of external triggers and the constancy of depressive disorder. As such, the juxtaposition of traditionally time-varying neurological data and the fixed nature of depression diagnosis makes an assessment of the strengths of these two well-known, widely used signal analysis techniques imperative.

2. Electroencephalography (EEG)

2.1. Introduction to EEG data

In order to better understand how Fourier transforms and wavelet transforms are applied in the analysis of EEG data, a basic understanding regarding the qualities of EEG and EEG interpretation must first be established.
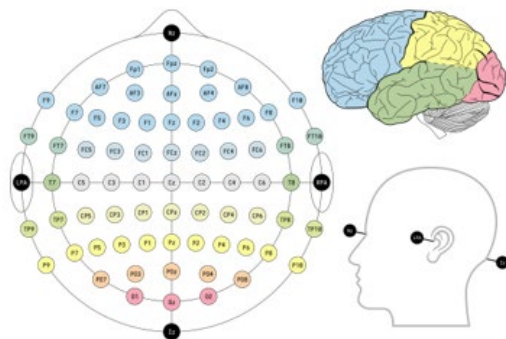
Figure 5: *10-10 electrode configuration diagram*
(Krol, 2020)

As described in Section 1, EEG data is collected by attaching electrodes in some standardized configuration to a subject's scalp. One example of a commonly used electrode configuration, the 10-10 system, is shown in Fig. 5. The electrode locations are represented by the colored circles on the largest portion of the diagram. Each color electrode measures most directly the electrical signals in the respective same-colored part of the brain in the top-right corner of Fig. 5. The left-hand side of the image corresponds to the subject's nose and can be thought of as the subject's scalp viewed from above, whereas both images on the right-hand side can be thought of as the subject's head viewed from the subject's left-hand side.

In the brain, synaptic currents in neurons create minute electrical fields because of the flow of ions, much like how electrical fields are induced when electrical current flows through a rod. Even through the brain tissue, skull, skin, and other organic obstacles between the EEG electrode and the minute electrical fields inside the subject's brain, a large enough electrode on top of the scalp can detect the aggregate electrical field generated by tens of thousands to millions of neurons. Thus, every electrode records slightly different data from one general portion of the brain. Ultimately, the EEG output is a measure of the oscillations in the electric fields recorded by every electrode (Mike x Cohen, 2019).

One example of EEG data is shown in Fig. 6. The bottom horizontal axis represents the time at which the data are recorded and is typically labeled in seconds. The vertical axis represents the electrode field measured by each electrode attached to the scalp, with each electrode label corresponding to a unique signal. The vertical lines in the example EEG data represent markers that show the timing of particular events, usually in cases where the observer would like to see the ways in which the EEG data change after some trigger or stimulus.
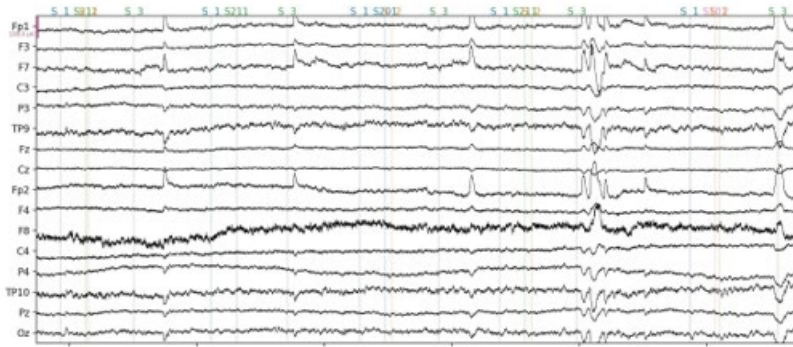
Figure 6: *Example EEG data (Newman, 2020)*

The data collected by EEG have both advantages and disadvantages. Regarding its advantages: EEG is relatively low-cost, is non-invasive while still being a direct measure of brain activity, and has temporal resolution and precision that can match the often too-quick speed of cognition in the human brain. The data produced by EEG are also surprisingly consistent across many species and on many scales of electrical-temporal activity. Finally, EEG results in very rich data that lends itself to many different types of physiologically inspired analyses.

Regarding the disadvantages of EEG: by its nature of measuring changes in large groups of neurons, EEG has poor spatial precision. The ability of EEG to record activity in areas of the brain deeper than the cortex is also limited. Moreover, because of the many facets of EEG data, it is time-consuming and complicated to analyze (Mike x Cohen, 2019).

The most important quality of EEG data is often considered to be its richness and variety. It is because of this richness that EEG data have the potential to be suitable to quantifiably diagnose depression. The biological mechanisms of depression are still relatively unknown, so it is prudent to begin quantifying diagnosis on a broader, whole-brain scale, rather than arbitrarily analyzing very specific parts of the brain. Once further research has been done relating depression diagnosis to specific areas of EEG and specific EEG frequency bands, researchers and doctors may want to look into the use of advanced computational methods (such as generative machine-learning algorithms), more specific but potentially more invasive neuroimaging techniques, or different data collection processes (e.g. fMRI, PET). Ultimately, the best solution for depression diagnosis may be one part a quantifiable combination of different technologies and data types, and another part still subjective self-assessment.

2.2. Interpretation of EEG data

When analyzing EEG outputs, one method professionals choose is to inspect historically pre-defined frequency bands in the resultant power spectrum that are typically referred to as alpha, beta, gamma, theta and delta waves. The strength of these predefined frequency bands as a biomarker for various neurological states has been established and confirmed in the past (Newson, 2019).

There are a number of ways to represent EEG data, whether that be analyzing all electrode channels through specific-domain graphs (e.g. time-frequency-power graphs), analyzing one or a few specific electrode outputs in their raw time-domain output as in Fig. 6, or other common representations. In this paper, both Fourier transforms and wavelet transforms are used to determine the powers of the specific frequencies present across all electrode channels. Using the known channel locations (as the data were collected using the common 10-10 electrode configuration described in Section 2.1), an average power spectrum of frequencies is plotted on a topographic map of the subject's brain. Then, topographic maps (also referred to as topoplots) of the average power level for each of the five frequency bands are created as well, to analyze the strength of the presence of MDD in further detail.
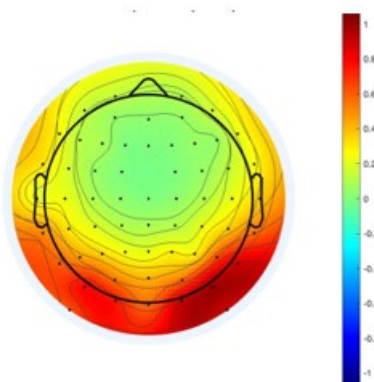
Figure 7: *Example topoplot (generated by author using MATLAB)*

Figure 7 shows one example of a topoplot generated by the author using the above process in MATLAB with the Fourier transform. One can view this topoplot as an image of the subject's scalp from above, where the nose is the triangular shape on top, the ears are the semi-elliptical shapes on the right and left, and the back of the head is the bottom of the image. The colored bar on the right-hand side of Fig. 7 is the scale used to quantify the colors shown in the topoplot, with warmer tones being higher powers and cooler tones being lower powers. Figure 8 shows a diagram of the major exterior regions of the human brain, with the prefrontal cortex (left-hand side of Fig. 8) corresponding to the top of the topoplot and the front of the subject's scalp, and the occipital lobe (right-hand side of Fig. 8) corresponding to the bottom of the topoplot and the back of the subject's scalp. The correlation between the topoplot and the portions of the brain leads to intuitive analysis. For example, one may notice higher powers (red tones) in the lower portion of the topoplot

above, signifying a higher presence of the specific frequency band being analyzed in the occipital lobe. This visual analysis is used in Section 4, in which a real dataset is analyzed.
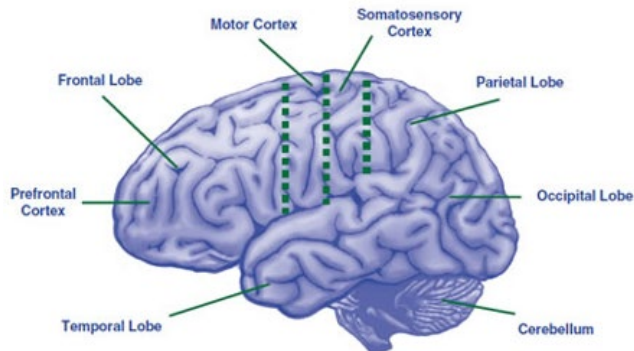
Figure 8: *Major exterior regions of the brain, labeled (Sousa, 2011)*

3. Signal analysis

3.1. Introduction to signal analysis in EEG

When considering EEG data, signal analysis is most prominently used in the data preprocessing and feature extraction steps of EEG analysis. In preprocessing, noise and artifacts are removed from the EEG data. Some examples of preprocessing steps that involve signal analysis include de-noising and applying band-pass filters to remove unwanted frequencies and ensure high quality data. Preprocessing is a fairly straightforward, well-established process, as its purpose is the removal of poor-quality data (Wang, 2023).

In feature extraction, signal analysis techniques, such as the two transforms discussed in this paper, are used to convert the complex EEG electrode data into a more suitable format for the purpose of analysis. Because of the many forms a "more suitable format" can take, and because of the many aspects of EEG data one may choose to focus on, feature extraction is a much more subjective area of signal analysis, and is thus the main focus of this paper (Wang, 2023).

3.2. Fourier transform (FT)

3.2.1. Math
The Fourier transform (FT) is a mathematical technique that transforms a function in the time-domain to a function in the frequency-domain. The inverse Fourier transform (IFT) does the opposite, transforming a function of frequency to a function of time. In this paper, the Fourier transform is used interchangeably with the fast Fourier transform (FFT), as the FFT is just a computationally faster method of performing the same transform. Likewise, the IFT and the inverse fast Fourier transform (IFFT) are used interchangeably as well.

This domain-transform is achieved by decomposing the original time-domain function, $g(t)$ into a sum of sine and cosine waves of different frequencies, then plotting the strength of each present frequency as a frequency-domain function, $G(f)$

Mathematically, the continuous FT is represented as:

1) $$G(f) = \int_{-\infty}^{\infty} g(t) \cdot e^{-2\pi i f t} dt$$

And the IFT is represented as:

2) $$g(t) = \int_{-\infty}^{\infty} G(f) \cdot e^{2\pi i f t} df$$

In the equations, $G(f)$ represents the frequency-domain representation of the signal, $g(t)$ represents the time-domain representation of the signal, f is the frequency at which the signal is being analyzed, and i is $\sqrt{-1}$. The FT and IFT output information in two dimensions, typically with either distinct frequency or time values on the horizontal axis and power on the vertical axis.

Note the periodic nature of the sine and cosine waves into which the Fourier transform decomposes the original function. The Fourier transform assumes a periodic nature to the original function as well, making it unsuitable to construct a non-periodic function from a small sample of the function's outputs. Despite this, the usefulness of Fourier transforms in analyzing periodic or entire sets of data is evident.

3.2.2. Fourier transform example

As a signal analysis process, the Fourier transform can be difficult to understand intuitively without an example. In this section, a sample function will be visually transformed from the time-domain to the frequency-domain and their respective graphs plotted for visual comparison.

The full code used to generate the Fourier transformed image can be found in Section 7. The function being analyzed is The second function being analyzed is

$$\frac{1}{\sqrt{2\pi\delta}} e^{-\frac{t^2}{2\delta^2}}$$

as shown in Fig. 9. This function is known as a Gaussian and is well-known to have a Fourier transform that is another Gaussian, which can be shown through the Fourier transform's mathematical definition. The function is arbitrary; its purpose is solely demonstrative.
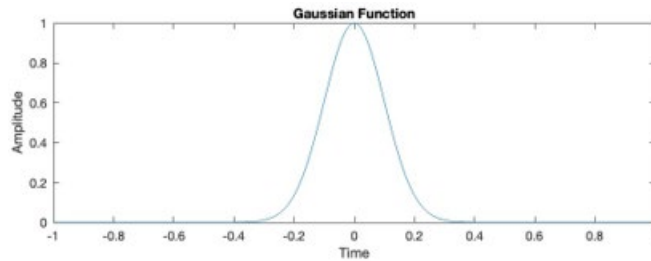
Figure 9: *Original signal in the time-domain (generated by author using MATLAB)*

Figure 10 confirms one's expectations of the Fourier transform by outputting another slimmer Gaussian. Although the conceptual definition of the Fourier transform can be more difficult to interpret in this specific example, one might do so by observing a higher presence of frequencies in the 0 Hz to 5 Hz range in the frequency transform of the original function. In other words, the frequency transform informs one that the Gaussian can be thought of as a continuous sum of sinusoidal functions with frequencies in the 0 Hz to 5 Hz, with each function present to a different degree (from a magnitude of 0 to approximately 250).
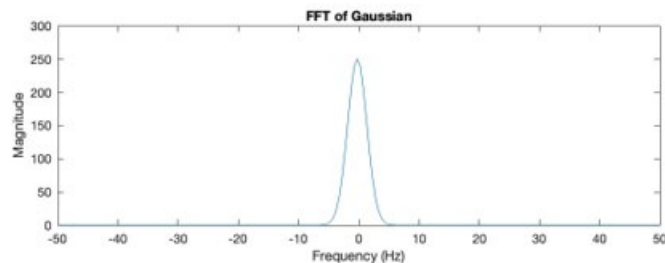
Figure 10: *Fourier transform representation of original signal in the frequency-domain (generated by author using MATLAB)*

3.3. Wavelet transform

3.3.1. Math
The wavelet transform (WT) is a mathematical tool that, like the FT, facilitates the analysis of signals by revealing their short-term frequency characteristics. There exists an inverse wavelet transform (IWT) as well.

Whereas the FT decomposes a signal into its constituent sinusoidal components, the WT decomposes it into a set of wavelets. Wavelets are small, localized, oscillatory functions. One example of a wavelet, the Morlet wavelet, is shown in Fig. 11.
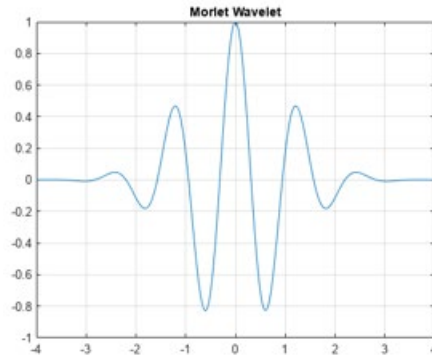
Figure 11: *Morelet wavelet (Morlet wavelet, 2006)*

In this paper, the WT is used interchangeably with the continuous wavelet transform (CWT). Likewise, the IWT and the inverse continuous wavelet transform (ICWT) are used interchangeably as well.

The CWT involves a process known as convolution, in which the wavelet is compared in small segments of time across the entire signal, as in Fig. 12, then scaled and shifted to search for a match to the signal at that particular position.
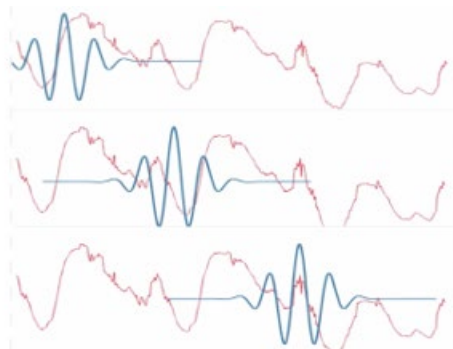
Figure 12: *Wavelet is convolved over the original function (Wavelet transforms in Matlab, n.d.)*

Mathematically, the CWT is represented as:

$$3)\ W(a, b) = \int_{-\infty}^{\infty} \quad g(t) \cdot \psi^* \left(\frac{t-b}{a} \right) dt$$

And the ICWT is represented as:

$$4)\ g(t) = \frac{1}{C_\psi} \int_{-\infty}^{\infty} W(a, b) \cdot \psi \left(\frac{t-b}{a} \right) \cdot \frac{da}{a^2}$$

In these equations, $W(a, b)$ is the CWT coefficient obtained from the wavelet transform, $g(t)$ is the time-domain representation of the signal, $\psi(t)$ and $\psi^*(t)$ are the function that describes the wavelet and its conjugate, respectively, a and b are the scale and translation parameters, respectively, and C_ψ is a constant that depends on the wavelet form used and normalizes the signal in the inverse transform. The value that represents the similarity of the wavelet with the original function scaled by a and at time b is represented by the right hand side of Eq. 3, $W(a, b)$. Thus, the CWT outputs information in three dimensions, typically with time values on the horizontal axis, scale on the vertical axis, and strength of correlation represented by different colors. Note that there is less of an obvious connection between the CWT and the ICWT than there is between the FFT and the IFFT, as the CWT and ICWT transform between different numbers of data dimensions.

3.3.2 Wavelet transform example

The full code used to generate the wavelet transformed image can be found in Section 7. The function being analyzed is the same as was analyzed above and shown in Fig. 9: $\frac{1}{\sqrt{2\pi\delta}} e^{-\frac{t^2}{2\delta^2}}$. Because the CWT naturally outputs a graph in terms of the scale of the wavelet while the FFT naturally outputs a graph in terms of frequency, the two resultant graphs are not easily comparable. Thus, the MATLAB "scal2frq" function is used to convert the CWT graph in terms of frequency. One expects the whole output to maintain a similar shape to the original function, with an absence of signals present when time = 0. On the horizontal-axis, one expects to see the same range of time as in the original time-domain function. On the vertical axis, one expects to see a range of frequencies. Finally, one expects to see a bar that represents the magnitude at which different frequencies are present.
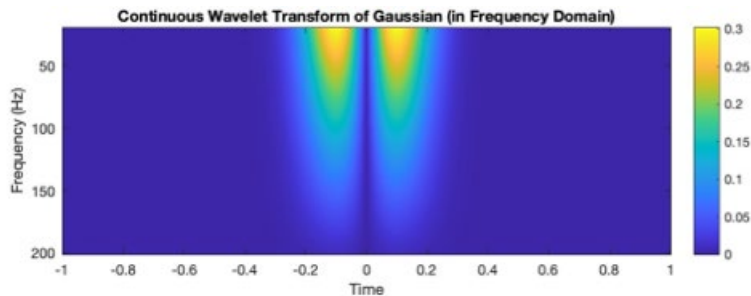
Figure 13: *Morlet wavelet transform representation of original signal in the time-frequency-domain (generated by author using MATLAB)*

Fig. 13 conforms to one's expectations of the resultant time-frequency-domain graph. Additionally, the CWT output is visually more "spread out" than the FFT output, a feature known formally as having greater spatial distribution. This is because of the necessarily lower precision that accompanies the CWT's ability to output both time and frequency information simultaneously. Note that although the CWT output is in terms of frequency, the 100 Hz to 800 Hz range of its frequency is different from the 0 Hz to 5 Hz range in the FFT-generated graph. This difference is compensated for in the power scale

on the right-hand side of Fig. 13, which ranges from 0 to 0.3 and indicates, like the vertical magnitude axis in Fig. 10, the degree to which each frequency is represented in the original function. Although the frequencies represented in the CWT graph are much greater than those in the FFT graph, they are represented to a lesser degree. Thus, it is clear that even when converting the CWT output from scale information to frequency information, a direct, quantitative comparison is difficult to achieve without multiple, complex conversion steps.

3.4. Preliminary comparison of techniques from mathematical and practical application

The most notable difference between the FFT and the CWT is the different domains and scales on which the two methods output data. This is the most crucial difference in actual data analysis, as it controls what features of the original data are focused on and how they are translated to frequency information. Because this difference is difficult to assess purely theoretically, it will be assessed in greater depth in Section 4 with an actual EEG dataset.

From a more practical perspective, there are some differences to consider between the two transforms. First, the FFT may be easier to use than the CWT due to its simplicity and ubiquity. Though the CWT is being used increasingly often, the FFT nonetheless has a longer history of use and has more literature regarding its usage. The FFT is also mathematically easier to understand and more straightforward to analyze, given its discrete two-dimensional nature. This difference can be ignored in scientific research and most professional settings.

The FFT is also computationally more efficient than the CWT because it analyzes the entire signal, rather than convolving over multiple scales like the CWT. This difference may be relevant in the future, should depression diagnosis with EEG data become significantly more widespread.

Moreover, it is clear in both example functions that the CWT output is more spatially distributed than the FFT output, as the inherent nature of the CWT plots data with more uncertainty and thus over more spatial area. This difference is relevant, as more spatially distributed data necessarily means a lesser degree to which the data can be interpreted and analyzed further. Although in the examples, this difference is offset by the additional time-frequency information the CWT outputs, this difference is likely a disadvantage when both the FFT and CWT are applied to the same output method, as in Section 4.

4. Comparison of FFT and wavelet transforms on EEG record

4.1. Introduction to the dataset

In this section, a visual comparison of Fourier transforms and wavelet transforms is demonstrated. In order to do so, both Fourier analysis and wavelet analysis are used to generate a topographic plot (topoplot) of the brain of one subject who experiences recurrent episodes of MDD from the power spectra of preprocessed resting-state eyes-closed EEG data taken from the subject. These data are from the article, "A mind-brain-body dataset of MRI, EEG, cognition, emotion, and peripheral physiology in young and

old adults" (Babayan, 2019). The anonymous subject is labeled as subject 010044. The presence of Major Depressive Disorder, as well as other patient characteristics, can be confirmed by the meta file containing patient specification data. The whole study these data was taken from is largely unrelated to the purposes of this analysis, but for further information regarding the study, the methods of data collection, and the methods of data preprocessing, one can visit the original source, which describes these characteristics in great detail (Babayan, 2019).

The purpose of this analysis is to visually compare the efficacy of Fourier transforms and wavelet transforms to confirm the previously established mathematical benefits and shortcomings of each transform type, as well as to compare the two analysis methods more specifically in the analysis of depression-focused EEG data with the purpose of improving depression diagnosis. Specifically, Morlet wavelets are used, given their long standing use in time-frequency decomposition, especially with EEG data. Given the continuous, resting-state nature of these data, both the continuous FT and the CWT are appropriate to use in this analysis.

4.2. Methodology

The full code used to generate the topoplots shown in Section 4.4 can be found in Section 7. This code is written in the most recent version of the MATLAB software as of September 9th, 2023, using the 2023.0 version of the EEGLAB software and the FieldTrip toolbox most recently updated on August 17th, 2023.

The resultant topoplots from the Fourier and wavelet analysis are solely analyzed qualitatively, based on pre-established knowledge regarding the correlation between the strength of specific frequency bands in certain parts of the brain and the existence of MDD. As such, the power levels corresponding to the FFT- and CWT-generated graphs visualized in Section 4.4 are not modified to both use frequency, as the examples are in Section 3, nor are the graphs adjusted to account for the difference in the power level magnitudes (e.g. normalizing or plotting both sets of power values on a logarithmic scale). From the author's analysis, the visual outputs of scale-focused, frequency-focused, and normalized CWT and FFT graphs are all very comparable, thus the difference in power levels should not affect the qualitative analysis in this paper. More discussion surrounding the challenges in quantitative analysis specifically with this project can be found in Section 5.2. Nonetheless, additional code written by the author to output normalized, frequency-focused topoplots using both transforms is available in Section 7.

4.3. Output with FFT versus output with CWT.

Figure 14 shows the topographic maps of the overall power spectra over all frequencies. The topoplot on the left uses FFT, while the topoplot on the right uses CWT.

Figure 15 shows topographic maps of the power spectra in specific frequency bands, again with the FFT-generated topoplot on the left, the CWT-generated topoplot on the right, and the frequency band being analyzed specified on the left of both topoplots in each row.
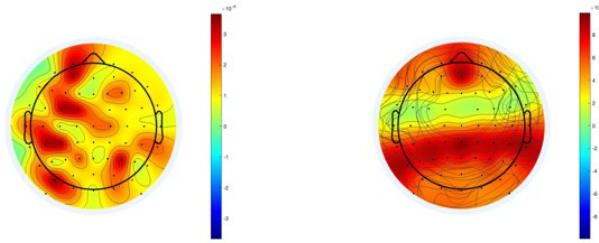
Figure 14: *Left: topographic map of average power spectrum in depressed patient created using FFT analysis; right: topographic map of average power spectrum in depressed patient created using CWT analysis (generated by author using MATLAB)*
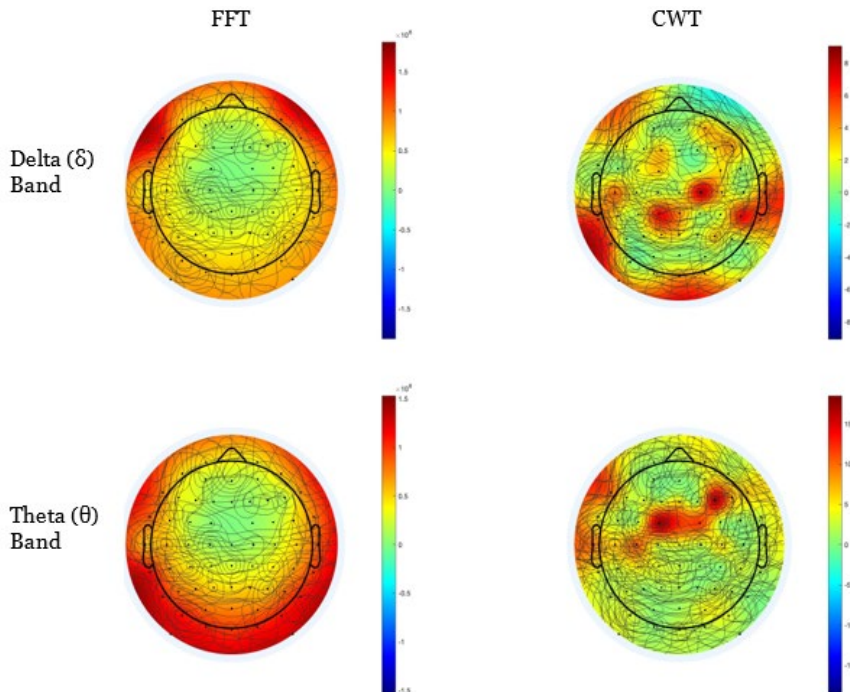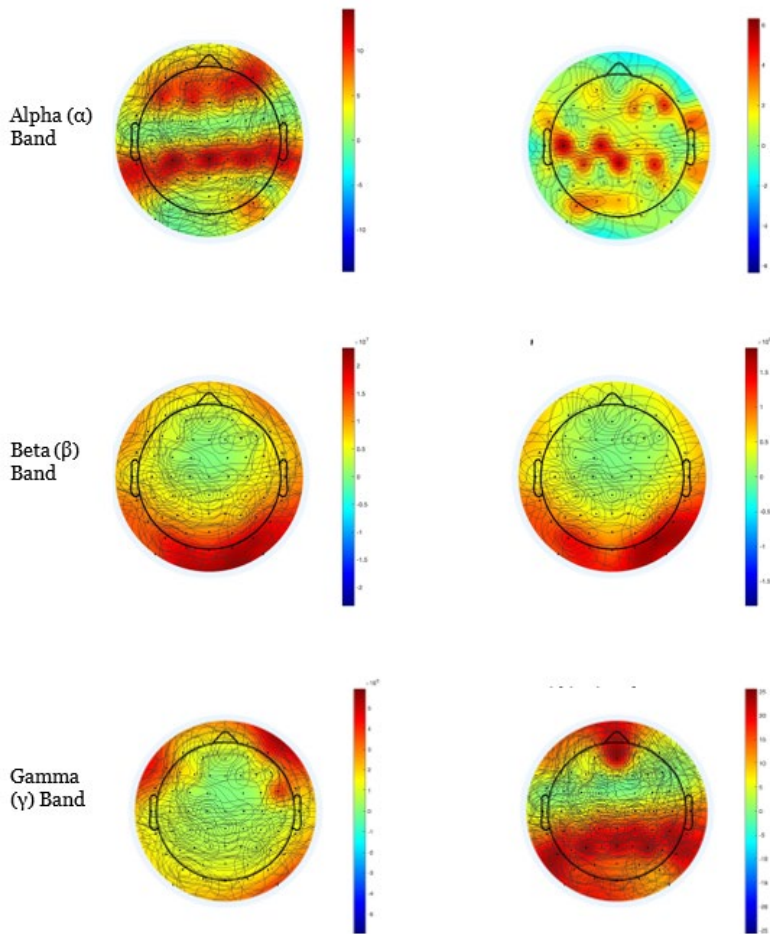
Figure 15: *Topoplots for specific frequency bands, with band name specific on the left. Left: topoplot created using FFT analysis; right: topoplot created using CWT analysis (generated by author using MATLAB)*

4.4. Qualitative comparison and further analysis of signal processing techniques

There are some visually evident differences between the two outputs. Some of these differences are indicative of the potential benefits and shortcomings of Fourier transforms compared to wavelet transforms.

First, there are some visual differences that are non-unique to EEG data or the presence of MDD. Some of the difference between the two topographic plots can be attributed to the different ways in which FFT and CWT process temporal variability. Due to the unchanging nature of FTs, Fourier-based topographic maps provide a static view of power distribution across frequency bands. In other words, they do not capture how the data may change over time. On the contrary, wavelet topographic maps depict the potential time-varying nature of the power distribution, meaning that one may observe

some short-term oscillatory patterns only present in the wavelet plot, creating more variation over the whole wavelet plot. This point is not as relevant for resting-state EEG data analysis, as there is no reason for the data to change over time in this scenario, but in the analysis of how depressive brain activity changes (e.g. after applying different triggers), this is one important benefit of CWTs over FFTs.

The CWT plot is also more spatially distributed than the FFT plot, as can be seen in its higher number of peaks, especially in the delta, theta, and alpha bands. This indicates that EEG power reads as more spread out over multiple brain regions with CWT analysis. This aligns with one's expectations, as established in Section 3.4. Fourier-based maps focus on power at specific frequencies, whereas CWT maps can show broader patterns of power distribution across both frequencies and time.

Somewhat surprisingly, no difference in noise and artifact sensitivity can be seen in the two plots. Because Fourier-based maps consider all data points simultaneously, one would expect the Fourier-generated topoplot to be affected by noise and artifacts to a greater degree than the wavelet-based topoplot. However, this is not the case, as there are no unexpected frequency spikes in either set of topoplots. It may be the case that this dataset is too clean to effectively assess the degree to which different transform-generated topoplots are affected by noise and artifacts.

With regards to depression diagnosis specifically, one method of analyzing the strength of each transform is observing dominant frequency bands that correspond to specific brain regions that correlate to the presence of MDD. To understand the locations of the brain regions specified in the following analysis, one can refer back to Fig. 8 in Section 2.2.

In the delta band, which ranges from 0.5 to 4 Hz, higher delta power in frontal regions has been correlated with the presence of MDD (Newson, 2019). This higher delta power can be seen in Fig. 15 in the CWT plot. The frontal lobe area has a zero or near-zero power level in the FFT plot of the delta band.

In the theta band, which ranges from 4 to 8 Hz, higher theta power in frontal regions has been correlated with the presence of MDD (Newson, 2019). This higher theta power can be seen in Fig. 15 in the CWT plot. The frontal lobe area has a zero or near-zero power level in the FFT plot of the theta band.

In the alpha band, which ranges from 8 to 13 Hz, greater alpha asymmetry and higher alpha power in occipital regions has been correlated with the presence of MDD (Nystrom, 1986; Prinz, 1989; Baskaran, 2012). With regard to alpha asymmetry, the CWT plot is clearly more asymmetric than the FFT plot. However, with regard to alpha power, higher power is most evident in the FFT-generated topoplot, with a high concentration of alpha-band frequencies in the back portion of the brain. Some higher alpha power in the occipital region is visible in the CWT-generated topoplot as well, but not to the degree seen in the FFT plot.

In the beta band, which ranges from 13 to 30 Hz, an overall increase in absolute beta power has been correlated with the presence of MDD (Newson, 2019). Because an overall increase in power would affect all parts of the resultant topoplot similarly, rather than causing higher power levels in certain regions, it cannot be assessed through qualitative analysis of the topoplots in Fig. 15. Thus, the author chooses to disregard the beta band in this analysis.

In the gamma band, which includes all frequencies above 30 Hz, reduced gamma power in the anterior cingulate cortex (see Fig. 16) and increased resting complexity of

gamma signaling in the frontal and parietal cortex have been correlated with the presence of MDD (Pizzagalli, 2006; Akdemir, 2015). Reduced gamma power in the anterior cingulate cortex relative to other regions of the brain is most clearly seen in the green (low-power) area slightly above the center of the topoplot in the CWT graph. Neither the FFT nor the CWT plots seems to show significant increased resting complexity of gamma signaling in the frontal or parietal cortices, as the resultant plot is fairly smooth and homogenous.

Figure 16: *Diagram of the anterior cingulate cortex as viewed from a subject's left-hand side, with the subject's nose on the viewer's left and the back of the subject's head on the viewer's right. (Hall, 2011)*

5. Conclusion and further research

5.1. Conclusion

As a whole, both the Fourier transform and the wavelet transform have their respective strengths and weaknesses in the analysis of EEG data for the detection of Major Depressive Disorder. The FFT has traditionally been used to analyze the type of continuous, resting-state data one is likely to collect in a clinical setting and has a longer precedent of use than the CWT. However, in the analysis of typically non-periodic, complex EEG data specifically, the CWT has recently seen more use due to its ability to output both time and frequency information simultaneously. Nonetheless, the most important practical difference between the FFT and the CWT stems from this ability. CWT outputs are typically more spatially distributed than FFT outputs, which can lead to CWT outputs being less precise. While this difference was confirmed in this paper, the greater spatial distribution of the CWT was not particularly detrimental to the subsequent analysis of the CWT output. Thus, each type of signal processing technique has its own historically- and practically-based benefits.

Moreover, to the degree analyzed by this paper, the CWT is generally stronger than the FFT at detecting depression biomarkers. In both the delta and theta frequency bands, the CWT is somewhat stronger at detecting higher frontal region power levels, which are indicative of depression in these two frequency bands. In the alpha band, the CWT is somewhat stronger at displaying asymmetry in power levels over the whole brain, but the FFT is somewhat stronger at detecting higher power levels in the occipital region

of the brain. In the gamma band, the CWT is significantly stronger at detecting lower power levels in the anterior cingulate cortex. The beta band is excluded from this analysis because of its difficulty of analysis using purely qualitative methods.

5.2 Further research

There is substantial room for further research in both the breadth and depth of this paper's findings, as well as in the ways in which EEG can be used to further objective depression diagnosis efforts.

This paper compares two signal-processing techniques, Fourier transforms and Morelet wavelet transforms. Other signal-processing methods, such as the spectrogram, Hilbert-Huang Transform, and time-frequency decomposition techniques should be explored and detailed, so that experimenters deciding which signal-analysis method to use will truly be able to choose the most optimal for the purposes of their experiment.

The paper is also limited by the data analyzed in Section 4. Most notably, because the only individual in the dataset with both MDD and good-quality data also had relatively high levels of recent alcohol consumption, the resultant EEG data (and topographic map) may be confounded by this factor. More broadly, because only one individual was analyzed, their analysis may not necessarily reflect the typical analysis of EEG data with FFTs and wavelet transforms. Using more data points would establish a multi-faceted understanding of both the qualities of the two transforms as well as the way in which depression can be considered in the analysis of a resultant topographic plot graph.

The analysis in this paper is also qualitative rather than quantitative. One aspect of the project that makes quantitative analysis challenging is the difficulty of translating both the FFT-transformed output and the CWT-transformed output to both be in terms of frequency and to display comparable power levels. Although the CWT output can be put in terms of frequency rather than wavelet scale and normalized, as can be referenced in the code in Section 7.2, the magnitude of the power levels displayed in the CWT topoplots is still somewhat smaller than the magnitude of the power levels displayed in the FFT topoplots. These variations in power scale are to be expected. Fundamentally, there are many factors that affect the power levels of the outputs of the two transforms, some being the choice of scales in the CWT analysis, the number of frequency bins in the FFT analysis, and the choice of wavelet for the CWT analysis.

Regardless, it is true that pure qualitative analysis may lead to imprecise comparisons. However, visual analysis is sufficient to achieve the purpose of this paper, which is to understand the differences between the FFT and the CWT in EEG signal analysis specifically for depression diagnosis. In the future, the author plans to improve their findings by quantifying the differences between FFT and CWT through statistical analysis. One method may be to analyze both healthy and depressed datasets and quantify the significance between the representations with both FFT and CWT.

With regard to the future of EEG data in depression analysis as a whole, more exact data collection methods could be used to assess specific areas of the brain. Some examples of these data collection methods may include high-density EEG (hdEEG), the more invasive intracranial EEG (iEEG), and a combination of EEG and function magnetic resonance imaging (fMRI) known as simultaneous EEG-fMRI. Similarly, advanced algorithmic methods may be used to strengthen the correlation between certain data and the presence of MDD. For example, machine learning could be used to recognize patterns

in data. At an even more advanced level, generative AI could be used to assess depressive disorder and some form of EEG data on an individual level, especially given the idiosyncratic nature of the brain. Eventually, the author hopes to explore the feasibility of real-time EEG-based depression monitoring and its practical implications for clinical settings.

6 Appendix

The code the author uses to generate the images shown in the paper can be found here: https://github.com/VNVI73/pioneer-2023.git

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Colonialism and the Anglo-Chinese Curriculum in 19th-Century Hong Kong

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1. Introduction

In 1835, Thomas Macaulay, as President of the General Committee of Public Instruction in India, decided to resolve the increasing divide within the committee by drawing up his *Minute On Indian Education*, which argues for governmental support for only Western-style education instead of vernacular education. Claiming "a single shelf of a good European library was worth the whole native literature of India and Arabia," Macaulay (2003, p. 230) sees the introduction of the English language as a gift from the superior European power to civilize Indian people. Macaulay's infamous proposal marked the initiation of a prolonged debate between two divergent opinions: Anglicist opinions, which advocate for the promotion of the English language and Western knowledge, versus Orientalist opinions, which favor the vernacular education taught in the local tongue and accorded with ancient traditions. The Anglicist-Orientalist debate featured the whole history of Indian education under British rule and inevitably influenced the educational policy in other British colonies, though in different ways. While an avid policy of Anglicization characterized British education in much of Africa and India, the colonial government in Malay and Hong Kong was more cautious about vernacular education (Griffiths, 2021, p. 132).

There is much debate about the intention of Anglicist or Orientalist education in colonial society under British governance. One prevalent theory is cultural imperialism. Historians who consider education a pillar of cultural imperialism argue that Western education, as part of the system of cultural hegemony, was imposed upon the native population to maintain the unequal relationship between the colonizer and the colonized. According to Carnoy (1977), British educational policies in India and West Africa aimed to consolidate political control by producing a class of English-speaking middlemen and to transform the local economy into a part of the capitalist system by training a docile population of workers. A subset of this theory is linguistic imperialism. In his book Linguistic Imperialism, Phillipson (1992) points out that the promotion of the English language in a colonial society creates an unequal status between English and the native languages. The colonial policy produced a dominant ideology of English as "the master's language," thus making the native culture inferior (ibid., pp. 110-128). Also, Pennycook (1998) interprets the seemingly competing Anglicist and Orientalist ideologies over education in Malay and Hong Kong as being complicit with British

colonial governance. By restricting access to English, the colonial policy in Malay and Hong Kong shaped English as a language of social prestige. In this essay, to challenge the belief that education in colonial society was solely molded by Western imposition, I will investigate the education aims of several parties and analyze how their attitudes towards education shaped the Anglo-Chinese curriculum in 19th-century Hong Kong education with two main arguments.

First, although many scholars notice the variability of British policies on education, there is not a strictly coherent objective behind such variability appearing in the Hong Kong colonial government's policies. The discrepancies between the views of the Colonial Office and the needs of the colonial government as well as between the colonial government and the Western educators hindered the formation of unified purposes behind the governmental policies. This paper only identifies one main aim of Anglo-Chinese education in Hong Kong – to nurture a group of bilingual middlemen, who could work not only in Hong Kong but also in China and was assumed to spread British influence in China. As the conjunction among various interests, this aim corresponds with Hong Kong's status as an entrepot in the Far East and a military and commercial hub for imperialist advance in China, and stands out to be a constant theme in 19th-century education.

Second, Hong Kong education is a complex product with multiple agents. Colonial education cannot be conceived as solely manipulated by colonial authorities; rather, two other social groups - Christian educationists and Chinese people - are also involved in the struggle for constructing colonial schooling. Even though the colonial government (as well as the missionaries) acted as the educator and the Chinese people as the educated, the asymmetric relationship did not impede the collaboration or resistance between these groups of power.

The term "Anglo-Chinese curriculum" is defined as the coexistence between a Western curriculum and a vernacular one in the same school. Divergent in instructional content and teaching methods, these two curricula were often taught separately by different groups of faculty. Two other types of Anglo-Chinese education are also discussed: 1. the schools that mainly focused on Chinese teaching with Western subjects in addition (examples include early "government schools") and 2. the schools that concentrated on Western curriculum with Chinese courses in addition (examples include Queen's College after the 1890s). These two types of schools showed a preference towards one particular curriculum but still reflected how Anglo-Chinese education evolved under different powers. In addition, in this paper, a large portion of the analysis of the curriculum will be given to English or Chinese language teaching, in that much of the Anglo-Chinese curriculum had been devoted to teaching students languages and that in the late 19th century much debate about education among different powers concentrated on language issues. Therefore, in the following paragraphs, this essay will follow a chronological order from 1842 to the 1900s to indicate the evolution of the Anglo-Chinese curriculum and discuss how the changes reflect the contestation between different demands from the government, the missionaries, and Chinese parents.

2. Early Period of Hong Kong Education (1842-1860s)

2.1 Vernacular Education

The history of Hong Kong education starts with the indigenous Chinese curriculum. The earliest schools on Hong Kong Island attested by Europeans were small village schools based in local temples and sponsored by the rural community, which focused

on basic reading and writing, while large study halls and more temple schools dedicated to more advanced studies can be found in Kowloon and New Territories (Sweeting, 1990, pp. 88-89). The village schools preserved much of the traditional teaching based on Confucian classics and continued to exist after the advance of British colonizers.

These vernacular institutions, though sparsely distributed, were influential in village affairs. As shown by early records that designated village schools through location and ethnicity (Punti, Tanka, Hakka), these schools mainly served children of local residents instead of immigrants who flocked into Hong Kong only after the Opium War. The work of local historians and anthropologists like Sung (1974) reveals that village schools in Hong Kong were closely related to the ancestor hall, the assembling space in the rural area. Either set in the hall or built in its proximity, these schools were sponsored by the local gentry who considered giving free education, as a charitable act, as important as celebrating their ancestors. Usually, the gentry would also offer funds to the students who succeeded in the Imperial Exams. Such sponsorship allows the gentry to exert their leading influence over the native population through charity.

2.2 Missionary Education

After 1842, European missionaries desiring to convert the Chinese population flocked to Hong Kong in order to build up the frontier of their mission work. Consequently, several mission schools, the earliest including the Morrison Education Society School, the Anglo-Chinese College, and St. Paul's College, were established in the first decade after the advent of Britain.

The primary objective of mission schools in Hong Kong was to train indigenous ministers who could assist in proselytizing the Chinese population, and great emphasis was placed on students' bilingual ability. Therefore, missionary educators give the same weight to the traditional Chinese curriculum as to Western education. In the Morrison Education Society School, the first mission school in Hong Kong, equal amounts of time were devoted to the Chinese curriculum and the English one, respectively (Chinese Repository, July 1843, p. 362). Even though missionaries wrote pamphlets to help beginners to study Chinese characters, the majority of Chinese studies still followed the traditional way of instruction under a Chinese master (Leung, 1987, pp. 116-123). In the Anglo-Chinese College, the headmaster James Legge, a famous sinologist who translated many Chinese classics into English, even used Mandarin to teach theological content in the seminary class for older students (as cited in Sweeting & Vickers, 2007, p. 12).

Missionaries often held negative opinions about the Confucian curriculum and the Chinese language, and some of them may even instill these supremacist views into the curriculum. For example, Samuel R. Brown, the headmaster of the Morrison Education Society School, despised the Chinese culture, claiming "nothing […] can be gained from [Chinese] native soil" (Chinese Repository, October 1842, p. 550), and attributed the stagnation of China to the nature of its mechanical education: "The mind of the nation has been systematically taught not to think, and the reasoning faculty, like their written language, has long ago been arrested in its improvement" (Chinese Repository, October 1842, p. 546). Such criticism of the ossification of Chinese education was often echoed by later educators in Hong Kong, and accorded with contemporary British depictions of Chinese civilization as static and submissive. Furthermore, according to Smith's study of teaching materials in the Morrison Education Society School (1977, pp. 16-32), students were indoctrinated with Western interpretations of the politics and religion in China, and

the essays written by the students often depict the Chinese people as dark, foolish, and Bible-less and their government as corrupt and stagnant, which corresponds to Brown's views of China.

Yet, despite his orientalist views, Brown still insisted on students' Chinese identity – those who graduated from the mission school will surely "return to their own people" and "still be Chinese" (Chinese Repository, October 1841, p. 583). Thus, in his 1841 report, Brown emphasized the importance of teaching the Chinese curriculum so that students could be respected among his people for their literary attainments and "transfuse […] the knowledge which they derive from foreign sources" to a larger population. (ibid., p. 584) And, as mentioned above, the vernacular curriculum was retained in Brown's school. Smith describes Brown's approach as "an educational imperialism" (1977, p. 32); however, studying two fundamentally different curricula, students were molded into mixed beings affected by both Confucian and Christian streams. Here, cultural hubris succumbed to the actual needs of the mission.

2.3 Government Policy on Vernacular and Mission Education

During the first two decades of Hong Kong's colonial history, the colonial government followed the longstanding tradition of educational voluntarism in England and made little intervention in both vernacular and mission schools. Although later in the 1850s the government incorporated many Chinese schools under the supervision of the Education Committee appointed by Governor John Francis Davis (1844-1848), the committee was still left to the hands of missionaries.

The majority of the limited funds for education went to the scholarships given to students in vernacular schools. An important factor behind the support for vernacular schools and their students was the government's desire to quell social unrest and conciliate with native inhabitants. The 1849 education report stated that the provision of education was a "most effectual means to conciliate the native inhabitants, and to render our Government popular among them" (as cited in Evan, 2006, p. 296). As mentioned in Section 2.1, village schools were considered by Chinese people as crucial in rural affairs, and the colonial government's scholarship functions similarly to local landlords' sponsorship of local schools and students in showcasing their support for indigenous people as well as the alliance with the gentry class. This intention echoed the British policies of stabilizing the social order and establishing British authority to attract Chinese merchants in the 1840s and 50s (Carroll, 2005).

While this aspect of colonial governance could be compared to the vernacular-oriented education policy in Malay and India, the Hong Kong government's purpose was more ambiguous, if its empowerment of missionaries is considered. Although the mission schools did not receive public funds from the government, much power over education had been given to the Education Committee, which was mostly occupied by Christian educators, such as Legge and Rev. George Smith, a teacher at St. Paul's College and an Anglican bishop of Hong Kong. While maintaining the principle of non-interference in local village schools, missionaries in the Education Committee put forth their ideals of promoting Western knowledge and religion in China through the introduction of bible study and the English language in vernacular institutions. Ernest John Eitel (1890-1891) mentions that several Chinese Christians were appointed to different village schools to instruct Bible reading and English learning and that in 1854, scholarships were set up for "great efficiency in Scripture knowledge and English language." Therefore,

Christian missionaries were the major providers of education, while the government's indifference towards education led to support for both mission schools and vernacular ones.

3. "Anglo-Chinese Balance" Period (1860s-1878)

3.1 Introduction of Western Curriculum

The introduction of Christian study and the English language by the Education Committee initiated the promotion of the Anglo-Chinese curriculum in vernacular schools, yet this was only done for a few students in government schools in the urban areas with the majority of village schools remaining purely Chinese schools. In addition, the Western curriculum in these government schools was confined to rudimentary English and Biblical knowledge taught by Chinese teachers, a fact that James Legge deemed as poor in quality in his 1860 report (as cited in Evans, 2006, p. 5). Thus, the Anglo-Chinese education designed by the Education Committee had been unstable and still traditional Chinese education at its core.

A larger sector of Anglo-Chinese education was made possible only after Legge's Scheme was proposed in 1860 with its emphasis on the English language. James Legge, who was a member of the Board of Education (which replaced the Education Committee), sub   mitted a scheme of concentrating five government schools into one large Anglo-Chinese school. With permission from the colonial government, the Central School was created and has been considered as the inception of public education in Hong Kong.

Instead of being dominated by Chinese studies, the curriculum in the Central School was evenly divided between Chinese lessons and English ones. In the annual report of 1865 on education, Fredrick Stewart stated that students devoted "four hours a day to English and four to Chinese" (Hong Kong Blue Book, 1865, p. 277). This English curriculum largely resembled that of day schools in England. For textbooks, Stewart mentioned a general list of materials that prevailed in the Irish state education and the British voluntary education, such as "the Irish National School Books and the Translation into English of portions of the Chinese Classics form, with the ordinary branches of all National Schemes of education," all of these under the instruction of a few European masters (Hong Kong Blue Book, 1866, p. 279-280). The translation of Chinese Classics into English indicates the continuing image of Chinese teachers' incompetence and the wish to replace them with European masters. However, this plan had not been adopted, and the Central School continued to recruit Chinese to instruct the Confucian curriculum.

The initial motive behind such change came from the continuing influence of missionaries. The first two decades of Hong Kong were characterized by social upheaval and an unstable population: the frequent movement of the Chinese population between the Mainland and Hong Kong made the census in the 1840s and '50s extremely difficult. As a result, the first mission schools could not ensure regular attendance of Chinese pupils, and all failed to attain their aims of producing local priests, which stimulated many missionaries to concentrate more on the potential of public education for their "enlightening" ideals. Legge, who proposed to create the Central School, suggested making English a more prominent part of the new school in his scheme in that "an influence may go forth from the Island, which shall be widely felt in China enlightening and benefiting many of its people" (Hong Kong Government Gazette, 1861, p. 106).

However, instead of a plan for a British public school, Legge's scheme was

envisioned only as an improvement of the current Anglo-Chinese system and was thought to facilitate both Chinese and English studies: not only "the English education would be more efficient" but also "an impulse would be given to the Chinese education carried on in the concentrated schools," whose influence would later diffuse into Chinese education in village schools (ibid., p. 107). Legge was vague concerning the extent of English education by only proposing that "well-educated" young Chinese scholars "would be found to enter English classes" (ibid., p. 106). Nevertheless, the fact that only students in higher grades with excellence in Chinese subjects were admitted to English classes makes it clear that the Central School was made to be a more effective Chinese school with an adjunctive Western curriculum.

3.2 Attitudes of Chinese Parents

The newly created Central School was more successful than other institutions in Hong Kong before. Enrollment in government schools had rapidly increased after the 1860s. The number of students subject to government education grew from around 150 in 1855 to 1978 in 1886 (Evans 2006, p. 301). Much of this success owes to changes in the attitudes of Chinese parents. The demographics of the Chinese population in Hong Kong had been drastically altered in the 1860s, as Hong Kong got rid of its chaotic situation and emerged as a safer entrepot than Canton after the Second Opium War. Chinese compradors and entrepreneurs previously located in Canton and Shanghai began to settle in Hong Kong and formed a group of Chinese bourgeoisie; at the same time, foreign firms were attracted to start their business in Hong Kong, which had created plenty of occupations for interpreters and contractors.

  Under the circumstances, the economic advantages of learning the English language were more obvious and more recognized by the new middle class. Students who acquired the English language were more likely to be employed in occupations with higher salaries like compradors and interpreters – the 1870 report of education notes that, among 95 graduates, 40 entered business in Hong Kong and around Asia (Hong Kong Government Gazette, 1870, p. 116). Hence, a fervent pursuit of studying English prevailed, which was recorded by both educators and students. Fredrick Stewart, the Inspector of School, attributed "the comparative success of the Central School" to "English being convertible to dollars" (Hong Kong Blue Book, 1865, p. 277), while Cheng Tien-Hsi (1951), who enrolled in the Queen's College (renamed from the Central School) in the 1890s, noted in his autobiography that children were expected to acquire "a good knowledge of Chinese and then learn English in order to carry on their business or start new ones" (p. 42). This pragmatic need for the English language through education was also seen before, as a proportion of students in the mission schools aspired to be interpreters and compradors. As one of the earliest students in the Morrison Education Society School, Yung Wing (1909) stated that his parents sent him to study under European teachers primarily in the hope that he could make a living as an interpreter.

  It should be noted that Hong Kong still had a considerable rural population, especially after Britain acquired Kowloon in the Second Opium War, and the antipathetic attitudes towards Western-style education continued to be found in the villages. In the early 1870s, English teaching was introduced in one vernacular school under a Chinese master, but in the following years, enrollment declined with the Chinese master resigning, indicating that English was not favored, presumably because the language had less economic benefits out of Hong Kong's commercial hubs. Here a discrepancy between the opinions of the urban middle class and those of villagers appeared due to their divergent demands under different contexts.

3.3 Government Policy On Balancing Anglo-Chinese Curriculum

The government's attitude toward the Anglo-Chinese curriculum in the Central School was largely influenced by Fredrick Stewart. As the headmaster of the Central School and the Inspector of School from 1864 to 1878, Stewart advanced many ideals held by Legge. In his mind, the main task of the Central School was "teaching of English," with the teaching of Chinese "in subordinate to it" (Government Gazette, 1878, p. 53). Due to his dissatisfaction with the quality of English teaching in the Central School, Stewart excluded the elementary teaching of Chinese from the Anglo-Chinese curriculum and instead placed an entrance exam to ensure students' basic ability in reading Chinese. On the other hand, the Anglo-Chinese curriculum in the Central School was formalized to offer intense instruction of the English language. In the Hong Kong Grant-in-Aid Scheme implemented in 1873, schools in Class V (the Anglo-Chinese schools with a concentration in English, including the Central School and some mission schools) were stipulated to have the same standards in English examination as schools in Class VI (the European schools, including those exclusively for European students) (Government Gazette, 1873, pp. 188-189).

However, Stewart placed a careful balance between English and Chinese studies. As mentioned above, equal amounts were divided between two types of curricula. Stewart justified his arrangement for pedagogical reasons. First, he felt that students should master their own tongue before they acquire foreign languages: "Without [Chinese education], it would be difficult, if not impossible, for the boys to acquire the knowledge of their own language which is so necessary for the acquisition of another." In addition, while accepting students' pragmatic need to learn the English language, Stewart believed that students should receive a firm education instead of mere English training. In his letter in 1878, Stewart expressed his aversion "to mere parrot work" in some schools where pupils were taught "colloquial English by rote from a phrase-book" and insisted that the Central School should impart "a sound education" (as cited in Evans 2003, p. 193). Hence, the inclusion of Chinese education as well as other Western subjects such as geometry and history guaranteed that Anglo-Chinese schools would not teach merely "trade English."

Despite Stewart's despise of English for trade, it should be noted that the Western curriculum still attempted to fulfill the pragmatic demands of Chinese students. In the Central School, a large proportion of Western subjects were devoted to English learning, such as reading, grammar, composition, and translation (from English to Chinese, and vice versa). Much emphasis was given to the ability to read and translate, while the ability to speak was much ignored, which was complained about by later observers. At the same time, Chinese studies were simplified with three subjects – reading, writing, and speaking – and for reading, the textbooks prepared by a British committee substituted Chinese classics. In this circumstance, applying the Chinese language properly in formal situations, rather than interpreting Chinese classics, became the primary aim of such a Chinese curriculum. Such a curriculum, whether from the Western side or the Chinese one, prepared pupils to be interpreters and clerks in colonial Hong Kong, which precisely accorded with the aspirations of Chinese parents and students.

Pennycook (1998) argues that, although Stewart's view on education appeared more balanced and more enlightened compared to his contemporary educators, Stewart's policy in the Central School suited the colonial governance better than more extreme Anglicist or Orientalist policies. The policy favoring the

balanced curriculum avoided the problem of making a discontented class caused by a widespread English education as in India; on the other hand, a limited amount of English education was sufficient to produce bilingual intermediaries that a pure vernacular education could hardly offer. While he properly identifies the positive effects of the Anglo-Chinese curriculum in view of the general colonial policy, Pennycook misattributes the Hong Kong government's purpose, claiming that an ideal education for the colonial subject on this island should be "a vernacular education to the majority of the population in order to maintain social control and educate workers better able to work under colonial capitalism, and a bilingual education for a small élite" (ibid., p. 112). Here the opinion simply embedded the Anglo-Chinese education in Hong Kong into the patterns of colonial education in India. No doubt non-interference with vernacular education in the rural areas can be seen as a means to maintain social order; however, an Anglo-Chinese education was also viewed by Hong Kong colonial officials to satisfy the needs of native people. In his speech at the exhibition day of the Central School in 1877, Governor Arthur Edward Kennedy expressed his satisfaction towards parents' support for the Central School, which he deemed as "the only judges [...] of the education required by their children" (China Mail, 26 January 1877, p. 2). This is an example of how the colonial authority was aware of the demands from the native people. In a sense, such awareness can also be interpreted as avoiding conflicts with the local middle class in the urban areas. For the second part of Pennycook's argument, though Anglo-Chinese education certainly played an important role in molding the Chinese elite in Hong Kong, a subtle difference still exists: an   intermediary class was needed, but not so urgently as a group of individuals who could assist in spreading British influence in China. Like many of his successors and later educators, Kennedy valued the number of boys who entered British firms or governmental arsenals in China (like Foochow Arsenal) as a signal of educational efficiency (ibid., p. 2). Therefore, while the colonial government did desire to promote British influences in China, its acceptance of the Anglo-Chinese curriculum can be seen as receptive to demands from Chinese parents.

4. Anglicist Period (1878-1900s)

After the 1880s, Western curriculum began to gain dominance in the Anglo-Chinese curriculum in Hong Kong education. In this period, the colonial government adopted a more active Anglicist policy by not only promoting the Western curriculum but also separating the Anglo-Chinese curriculum. This development corresponded with the transformation of education in England. In late Victorian England, the government gradually abandoned its long tradition of voluntarism and elitism in education affairs and undertook the responsibility of providing education for the labor class as well as the middle class. Along with a state system of education, the textbooks and curriculum became uniform, with the southern variety of English coined as "the standard English," which is often considered as "linguistic imperialism at home."

Additionally, the Grand-in-Aid Scheme in Hong Kong provided an apparatus that made control over education feasible. After its introduction in 1873, the scheme was revised in 1879 to incorporate most mission schools under government sponsorship, which means that nearly most elementary and secondary institutions were subject to governmental inspection and a uniform system of examination. In this circumstance, the influence of missionaries on education faded, as the involvement of the government gradually increased.

4.1 Governor Hennessy On Promoting English Education

The first pressure to break the balance within the Anglo-Chinese curriculum came from Governor John Pope Hennessy (1877-1882). As the first governor who adopted a strong pro-English stance on education, Hennessy, after his visit to several village schools as well as the Central School, expressed his dissatisfaction with English education under Stewart's inspection and, in his speech at the prize day of the Central School, argued that the principal task of education in Hong Kong be "to increase the number of English speaking and English writing Chinese inhabitants of Hong Kong" (Hong Kong Government Gazette, 1878, pp. 26-29). Later in his dispatch to the Colonial Office, he made a stronger statement that in every government school, English should be taught so that Hong Kong "have here an English-speaking Chinese community" (CO 129/181, pp. 167-168).

At first glance, Hennessy's position seemed bluntly Anglicist; however, his attitude towards education should be connected to his close relationship with the Chinese elite in Hong Kong. During his governorship, Hennessy attempted to elevate the status of the Chinese community in a much more radical manner than all his predecessors, which received much gratitude from the native elite as well as resentment from the European colonists. As the first governor who paid a formal visit to Tung Wah Hospital, the representation of Chinese voices, he supported the autonomic organization for their contributions to arbitrating within the Chinese community and even promoted one of its directors, Ng Choy, as the first Chinese member in the Legislative Council. Yet, such efforts were countered by the European colonists who long insisted on segregation and excluded the native population from sharing administrative power. According to Lowe and McLaughlin (1992), the exclusion of Chinese was achieved largely based on language: by refusing to provide Chinese translation in the English-language press, the European community rendered most Chinese leaders unable to participate in public meetings or petition over certain resolutions. English speaking among the Chinese community was likely to be Hennessy's primary concern in education, which was deemed important in elevating the political representation of native people. Here beneath Hennessy's Anglicist attitude was indeed a pro-Chinese sentiment.

Hennessy's opinion stimulated the rapid Anglicization of the bilingual curriculum in Hong Kong. In February 1878, an Education Conference was called by the colonial government for the first time. Part of the resolutions at the conference includes: 1. The primary object of government education was the teaching of English; 2. The preliminary requirements in Chinese knowledge should be raised for all candidates for admission into the Central School; 3. 5 hours would be devoted to English lessons, while 2.5 hours would be devoted to Chinese lessons. Also, English lessons were made obligatory, and Chinese lessons were optional (Hong Kong Government Gazette, 1878, p. 90). In 1880, an Education Commission was appointed by Hennessy to evaluate the possibility of making the Central School a collegiate institution. Although the Education Commission refused the idea in their 1883 report, the paramount importance of English teaching was reiterated as the goal of the Central School.

In addition, with more time and an increasing number of British staff, the academic subjects in the Western curriculum were also expanded beyond language teaching. In the 1870s, chemistry, map drawing, Euclid, and algebra were introduced into the Central School. Then in the 1880s, Latin, Shakespeare, and Trigonometry were taught in the upper school of the Central School. On the other hand, the Chinese curriculum quickly shrank. After 1880, translation was left to be the only Chinese course in the upper school. In 1896, all the Chinese lessons in the lower school and

the preparatory class were formally abolished on the recommendation of the government.

4.2 Government Policy Of Anglicization and Disagreements

Behind the expansion of academic subjects lay the increasing attention to the longstanding imperial interest of Hong Kong education – to spread Western knowledge in China. Though often faded before the more urgent issues of English teaching in earlier periods, the emphasis upon Western academic curriculum was invigorated in the 1902 report of the Committee on Education, which maintained that that "the spread of Western knowledge is no less essential [than the spreading of English language]" (Hong Kong Sessional Paper, 1902, p. 379). The report recommended that in the Anglo-Chinese schools "Western knowledge should be taught systematically" in all classes and that "it should be taught in Chinese until the students have acquired so good an understanding of English as to enable them easily to receive instruction in English" (ibid., p. 380). The significance of students' Chinese knowledge was recognized, but only on the ground that Chinese learning in Western knowledge could not influence subjects under the Chinese Empire without good command of the Chinese written language. Here, translation, as the only Chinese lesson taught in the Queen's College, was suggested to "be seriously studied under competent teachers in all the classes" (ibid., p. 384).

However, it should be noted that the Anglicist policy promoted by the colonial government aroused disagreements and even resistance from different groups. One of these voices came from the Colonial Office. The metropole authorities, though generally supportive of promoting Western education, were nevertheless cautious about the large-scale Anglicization in education as well as the neglect of vernacular studies. In a series of correspondences regarding the Education Conference held in 1878, Sir Michael Hicks Beach, whose opinion represented the ruling of the Colonial Office, held an ambiguous perspective on the resolutions passed in the conference. While Hicks Beach approved the general conclusion that the teaching of English should be promoted, he criticized the resolutions as "somewhat too strongly worded in affirming that such teaching should be the primary object to be borne in mind by the government" (CO 129/181, p. 224). Additionally, Hicks Beach expressed his reluctance to accept the proposal of making Chinese optional by favoring Stewart's policy of Anglo-Chinese balance: "I consider that not less than four hours a day should be devoted to the study of Chinese for those who learn it [...] I do not therefore feel prepared to require that Mr. Stewart shall abandon his present method against his own judgment" (ibid., p. 456-457). Later British officials continued to emphasize the importance of vernacular education. In his reply to Governor Bowen (1883-1885), Lord Derby recommended that "such encouragement [of English education] does not result in the neglect of vernacular education" (cited in Evans 2006, p. 12). Here emerged the conflict between the British general policy on colonial education and the more radical action conducted by the colonial government.

Such a discrepancy between the metropole and the periphery continued to exist in the 1890s and 1900s, as the Hong Kong government advocated separate education for different nationalities. In its 1902 report, the Education Committee advocated for creating two new public schools for British children only and thus making the Queen's College for Chinese children exclusively. The decision was much stimulated by a petition signed by European residents in Hong Kong, many of whom could not afford private education in Hong Kong or studies back in England. The Committee's arguments for separate schools for British residents largely resembled

those that appeared in the petition. First, on a pedagogical ground, British children in the Anglo-Chinese schools were "retarded by the inevitably slower progress of their classmates, to whom English is a foreign language;" also, a racist opinion was expressed that British children must have suffered from "alien beliefs and other ethic standards" by mixing with Chinese children (Hong Kong Sessional Paper, 1902, p. 378). Although the proposal was approved by the Colonial Office, the Secretary of State for the Colonies, Joseph Chamberlain, insisted that this could be done only when demanded by a particular section of a community and opposed a general policy that "education should follow the lines of race" by stating that "I cannot consent to exclude any nationality from the main school of the Colony—the Queen's College" (Hong Kong Government Gazette, 1903, p. 485).

Another important influence came from the Chinese elite. From the 1870s on, a group of Chinese elites in Hong Kong had formed and consolidated their leading role within the Chinese community. The social organizations established by the Chinese elite, such as the Tung Wah Hospital and the Po Leung Kuk, went beyond their original functions as charity institutions and quickly became the center of Chinese affairs. On the other hand, the Chinese elite had many connections with the colonial government. As the colonial authority gradually recognized the role of local elite in maintaining social order in the 1870s and 80s, the automatic organizations were empowered to be quasi-government bodies, with native leaders recruited in the government or in the Legislative Council. Also, as compradors, interpreters, doctors, and lawyers, most of the members in the upper class had a background of English education in Hong Kong or abroad.

4.3 Influence Of Chinese Elite On Vernacular and Western Education

Many Chinese elites were often the most fervent advocates for the English language and Western curriculum, and their relationship with the colonial government rendered their opinions heard. Indeed, two Education Commissions in 1882 and 1902 both had the presence of the Chinese elite. In the 1882 report of the Education Commission, according to Evans (2003, p. 231), Ng Choy, the first Chinese representative in the Legislative Council and a member of the commission, argued that Chinese students should not waste time on the Chinese language, with which they were already familiar with, but should be confined to English studies, while other European members held a relatively moderate stance. Three signatories of the 1902 report of the Education Committee included Ho Kai, a lawyer and another Chinese member of the Legislative Council, although his influence on the report was unclear. Such a demand for English education was not limited to requests for the general Chinese community. The group of the native elite had also argued for better Western education for the children of their class. In 1902, eight prominent Chinese leaders, including Ho Kai, presented a petition that suggested the establishment of an English high school for the Chinese upper class. Similar to the one from the European parents, the petition from the native elite put forth their argument on both pedagogical and hierarchical grounds. First, government public schools were considered unsatisfactory in providing "a good English education" as well as a secondary education. Second, absolutely undesirable was "the indiscriminate and intimate intermingling of children from families of the most various social and moral standing" (Hong Kong Government Gazette, 1902, p. 236). As a result, St. Stephen's College was established in 1903 as a mission school, and the Church Mission Society (CMS) received funding from Chinese leaders to run the institution, for the high academic standards performed by other CMS schools like St. Paul's College as well as Chinese elite's acquaintance with Anglican missionaries.

The interests of the Chinese elite were not always consistent with the policy of the colonial government, however. This is most evident in the issues of separate education for different nationalities, which conflicted with Chinese insistence on racial equality. In 1902, Robert Ho Tung, a Eurasian comprador and a millionaire, made a donation to establish a government Anglo-Chinese school for children from all nationalities. In his reply to the Colonial Secretary, an emphasis was laid upon that "no distinction should be drawn as regards either the nationality or creed of any scholar applying for admission to the Kowloon School." (Hong Kong Sessional Paper, 1903, p. 471) However, ultimately this school was named Kowloon British School and was used to fulfill European parents' needs for a separate school, which was only reluctantly accepted by Ho Tung when the government promised that "the educational wants of the Chinese [in the Yaumati District School in the Kowloon peninsula] are well provided for" (ibid., p. 471). A letter signed by Wang Chung-yu expressed a stronger sentiment on this topic. By employing the philosophy of utilitarianism, the author warned that the policy of separate education may precipitate "mutual misunderstandings in Hong Kong" and "aggravate the hatred between Chinese and foreigners" (Hong Kong Daily Press, 7 February 1901, p. 3).

Chinese responses to the Anglicist policy on education in the late 19th century were not limited to being passive recipients of the English language and Western curriculum. Rather, such reactions can also take the form of resistance. As the colonial government rapidly reformed the curriculum in the government Anglo-Chinese schools, attempts to introduce Western knowledge in vernacular institutions were unsuccessful. As a result of the introduction of an elementary Western curriculum taught in Chinese in government vernacular schools, Eitel, the Inspector of School, had to shut down eleven Chinese schools for their bad attendance in 1893 (Hong Kong Sessional Paper, 1894, p. 190). As the government was more consciously retreating from supervising vernacular schools later, the Chinese elite filled the gap in providing purely Chinese education. Many Chinese associations, the most prominent being the Tung Wah Hospital, had established many vernacular schools, which were classified as Kaifong schools in the government report and exempted from governmental supervision, as part of their charity mission from the 1870s. By offering a traditional Chinese education on an elementary level, these Kaifong schools gained favor among the rural population in Hong Kong and expanded rapidly during the 1890s – as Eitel observed, the increase of scholars in education during this period was largely due to the free schools supported by Chinese residents (ibid., p. 189). In the 1900s, these Kaifong schools were reformed to follow the development of vernacular education in government schools and other mission colleges. Tung Wah Hospital Committee, for example, introduced new Chinese readers to textbooks used in China and Hong Kong in 1905 and established an examination system to qualify local teachers (as cited in Sweeting 1990, pp. 302-304). As such, the Chinese elite had not only been the receiver of education but also acted as the provider of vernacular education, and the colonial government and the missionaries no longer solely controlled Chinese education.

5. Conclusion

Education in 19th-century Hong Kong is a more complex product than what cultural imperialists suggest. An analysis of the bilingual curriculum in Hong Kong education reveals that both the colonizer and the colonized were involved in the shaping of education. In the early periods of Hong Kong education, the constitution of the Anglo-Chinese curriculum was largely determined by the pragmatic demands of the Chinese population. Later, as the colonial government increased its control over education

with an Anglicist policy, missionaries' dominance in educational affairs was replaced by governmental supervision, while the Chinese began to take over vernacular education in the private sector.

       In addition, the colonial policy on Hong Kong education cannot be seen as the promotion of Western education and the English language at the expense of native culture and languages in order to create and maintain an unequal relationship between the colonizer and the colonized. Nor was such a policy geared toward a type of colonial governance that, through Orientalist or Anglicist policies, aimed to produce a docile population. Instead, British laissez-faire attitudes in the early years of Hong Kong education led to little interference in educational issues, while later the effects of more intervening policies were limited by disagreements from other sides. However, another type of argument (for example Sweeting & Victor (2007)) that sees the colonial policy on education as a balanced measure based on liberal considerations also overlooks the primary motives behind the government policy. The basic aim of the educational policies lies in spreading British influence in greater China, and the Anglo-Chinese curriculum served to nurture a bilingual workforce that could work in the China Mainland. In the circumstances, the curriculum had stressed both English and Chinese languages, instead of ignoring the native tongues.

       Phillipson (2012) argues that 1. Western imposition of language policies on native people and 2. colonized people's active wish to acquire English are not a dichotomy but both contribute to a linguistic hegemony. It is true that such an imperialist presence is structural in culture, the media, and communication; however, these two patterns of imposition and reception are oversimplified in education. The example of the Anglo-Chinese curriculum in 19th-century Hong Kong suggests a more contextualized approach to investigate the relationship between British colonial governance and education in a colonial society.

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Poetry Translation in the Age of Machines via Julia de Burgos' "Río Grande de Loíza"

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Introduction

In modern times, translation has become fundamental to globalization in a variety of manners. One important example is through the circulation of literature, which, by crossing national and linguistic boundaries, has widened literary accessibility, allowing readers around the world to gain greater cultural knowledge and contact. However, the methodologies of translation—for instance, balancing word-scaled versus looser styles of artistic interpretation—have been a historic point of debate among scholars. Recent technological developments such as machine translation only complicate this, raising questions about the role of human translators themselves. This paper aims to discuss a few issues that arise out of the crossing of these two spheres. First, is it possible to measure a "successful translation," and if so, how? Second, are non-humans able to make creative decisions in translation-based problem-solving that meet these standards of success?

It should be said here, then, that the purpose of translation will be considered as the effort of preserving the writer's original voice while creating an alternative for those unfamiliar with the source language. What concerns me most in this regard is the preservation of that original voice, since there are many means and no singular end. An effective path to investigation is poetry, a form built base-up out of meticulous diction both suggesting and creating meaning. Voice in poetry, compared to voice in forms less concerned with linguistic technicality, is much more difficult to transfer from the source to the target language while upholding strong resemblance to its original identity. Some scholars go as far as to say that poems are impossible to translate. In this case, the standards for preserving voice—through a wrestling between both art and precision—are extremely high in the translation of poetry, making it a perfect diving board for the coming experiment.

For this paper, I have chosen a poem with a voice that is distinctly personal yet global, honored by the literary scene since its publication in 1935. Through its Puerto Rican sensibility, "Río Grande de Loíza" by Julia de Burgos holds an internal sense of globality—an identity reacting to colonial history—that lends itself particularly well to external globalization through circulation. Thus, it is crucial that the voice and vitality in De Burgos' language is carefully preserved as it is translated.

Through comparing various translations of this poem—from scholarly to machine-translated quality—it becomes clear that in light of relevant technological developments, the struggle of creative decision-making with an emphasis on vocality

remains necessary. That even while algorithmic translation expands in its influence and optimization, humanism—in particular, the artistic choices made by scholars—remains fundamental to translation as we view it.

Julia de Burgos and Río Grande de Loíza

As noted in translator Jack Agüeros' introduction to *Songs of the Simple Truth,* Julia de Burgos was known by many to be Puerto Rico's greatest poet. Influenced by the Post-World War imposition of United States citizenship onto Puerto Rico and the island's subsequent struggle towards independence, De Burgos spent much of her life composing works with intrinsically global themes (Agüeros). Her shortened pen name, in and of itself, is a grammatically incognizant phrase that reflects upon the state of her island, meaning Julia of Burgos, belonging to herself and no other (Rosario). "Río Grande de Loíza" was written when she was merely twenty-one years old and can now be found in nearly every anthology of Puerto Rican poetry.

The poem, centered around a major river in De Burgos' hometown, celebrates national identity through exploring the romance of the wilderness. As a child, the speaker stumbles upon a river that becomes the muse of her dreams and a large, internal entity. De Burgos creates a theme of containment, with the river being a powerful, flowing, and uncontained refuge compared to the ocean that arrests her homeland through colonial oppression. In "The Waters and the Wild," Bender suggests the possibility that De Burgos' was influenced by Puerto Rican folklore, where wild spirits stole children away from their sheltered civilization for a greater liberation (Bender). With Puerto Rico's imperial history lacking sustained national independence, it makes sense then that poets rebelled against the rigid and determined national identity with one full of natural unruliness and fluidity.

De Burgos describes the journey of the river alongside the journey of her own life, placing herself into the river and vice versa. The speaker's identity becomes entangled with her surroundings of water, hills, and skies until the river represents not only herself but her people—giving the poem political and cultural relevance. De Burgos portrays Puerto Rican identity as something both wild and beautiful and mobile, something self-containing its own history, allowing this poem to flourish with a sense of an intra-globality. As such, "Río Grande de Loíza" became known as a quintessential poem taught in Puerto Rican curriculum and, eventually, circulating around the world (Bender). This was done through translating it into various languages such as English, for which I will present the two most notable scholar-translated versions.

The English Translations

The first is Jack Agüeros' 1996 version from *Songs of Simple Truth,* a collection of over two hundred Julia de Burgos poems that Agüeros himself translated. A Puerto Rican poet, activist, and translator, Agüeros shared not only poetic identity but cultural and national identity, signifying the possibility of this work adhering to the sphere of Puerto Rican literature. *Songs of Simple Truth* contained both well-read and lesser-known De Burgos poems, holding a specific, scholarly audience due to its depth of materials, although it also attracted general Anglophone readers looking for an exhaustive examination of the poet's life collection. Thus, due to the heavy obligation and pressure of communicating De Burgos' art, it makes sense that Agüeros' style strives for technical precision in direct, word-for-word translation.

The second notable human translation of "Río Grande de Loíza" is Grace Schulman's 1994 version from Volume 17 of *Callaloo Journal*, an international journal focusing on the African diaspora. Compared to that of *Songs of Simple Truth, Callaloo's* scope reaches beyond an audience interested in the work of a specific Puerto Rican poet, transcending national boundaries to an international conversation between distinguished literary voices. The translation here is done by Schulman, an award-winning poet and professor. Looser in its linguistic interpretation, this version focuses more on playfulness with language and metaphor—which makes sense in context of its literary arts audience.

With both translations having been circulated through the internet and cited by scholars, it is worthwhile to examine the differences between the two. Agüeros' and Schulman's interpretations of this poem vary in voice due to diverging creative decisions made in word choice, and through comparing a few of these instances, we can showcase the translator's difficulties of succeeding in both precision and artfulness, as well as the influence of a translator in the preservation (or, perhaps, recreation) of voice.

From the beginning stanza, the two translations diverge immediately. Where De Burgos writes "alargáte en mi espíritu," Agüeros corresponds with "elongate yourself in my spirit" while Schulman translates "undulate into my spirit." "Alargáte" roughly means to stretch out in English, making Agüeros' word choice of "elongate" slightly more precise. On the other hand, Schulman's more creative choice of the word "undulate" might be consistent with the movement of the river, the central subject of the poem. Sonically, "elongate" resembles "alargáte" more closely than "undulate."

In terms of concision, "undulate" more tightly corresponds to "alargáte" as compared to the phrase "elongate yourself," but Agüeros using "yourself" depicts the river as stretching itself out inside the speaker's spirit, capturing the original reflexive form. He sticks with this reflexive clarification several times throughout the translation, showcasing his priority of maintaining grammatical equivalence over syllabic flow.

Additionally, Agüeros' use of "in" implies that the river might have had a former presence inside the speaker's spirit, while Schulman's version "undulate into my spirit" focuses on the action of surging in. The difference here was likely influenced by the grammatical structure of "en," which means both "inside" and "in," with "in" at times having a more active use as compared to inside. Seen through mere syllables in the opening line, both logistical factors present in the conversion between languages as well as the two translators' own creative intentions are at play in this process. Somewhere between Spanish and English, the original voice and meaning splinter off into variations that have been tinted by the decisions and voice of the translator.

The second stanza brings another distinct difference that alters not only the meaning within the line, but within the poem overall. In the seventh line, De Burgos writes "y esconderte del mundo, y en ti mismo esconderte." Subsequently, Agüeros translates this to "and to hide you from the world and hide you in yourself," while Schulman chooses "and hide you from the world in myself" (De Burgos). The original version suggests that the speaker yearns to hide the river from the world and in itself, with the river acting as a self-containing entity that acts as a refuge from imperial society and civilization. Agüeros, once again, takes this literally, forging an almost word-for-word translation. Schulman, on the other hand, *creates* a translation where the speaker attempts to hide the river—from the confines of society—within herself. While De Burgos herself does not indicate this in the line, Schulman works off the theme of the river and the speaker as objects that contain or become each other, which exists heavily in the original poem.

Another inconsistency between the two is in the first line of stanza eight. De Burgos describes the colors of the river: "Azul. Moreno. Rojo" (De Burgos). Agüeros translates this into three colors, "Blue. Brown. Red," while Schulman translates it into "Blue. Dark. Red" (De Burgos). "Moreno" in Spanish means both the color brown (though "marrón" is more popularly used) and dusty or dark-colored. It is interesting that in a list of colors, Schulman chooses the less obvious definition while Agüeros sticks with that first definition. However, as in the example of "in" holding a double meaning non-existent in English, neither translator is able to capture the full equivocality of "moreno," since there is no word in English that means both brown, dark, and dusty at the same time. This, then, is an example of something being lost in translation due to varying language structures.

Overall, it seems that Schulman prioritizes the preservation, or perhaps enhancement of metaphors and central ideas, allowing herself a looser margin in terms of semantics compared to Agüeros. Does this mean, exactly, that she is less successful in preserving the original voice of Julia de Burgos? While it may be true in contexts where the framework of language is more rigid, one must consider both the form of poetry and what constitutes the voice of the speaker. In Spanish, De Burgos' reverent tone and language attempts to capture the flowing water of the Río Grande, creating a wild, uncontainable image opposing the structure of colonial civilization. If her intentions were to move in tangent with the river, being one with the water, would Schulman's looser, less tight translation focusing on the metaphorical actually be favored by De Burgos over Agüeros' tighter one?

Holding no definitive answer, we discover that determining a translator's level of achievement in preserving the source material voice is more difficult than it initially seems, since there are countless interpretations but no singular set of standards. In "Translation of Poetry: Theory and Practice," Adam Czerniaski compares this to artistic reproductions of a portrait—charcoal, oil, and pencil create alternate versions that resemble the subject in different manners. However, he argues that this concept of resemblance is tricky in translating poetry. Czerniaski cites Polish poet Stanislaw Wyspianski, who viewed languages as being divided by their isolated sonic, grammatical, accental, and other constituents, influenced by the Whorf-Sapir thesis on the idea of language structures creating impenetrable walls of perception between cultures and the seeming discouragement of translatability (Czerniaski).

Additionally, in this assessment of "Río Grande de Loíza," it becomes clear—through the failure of upholding the double meaning of "moreno" and "en mi espiritu" in English, as well as through the established case of incongruence between two languages—that it is impossible to fully preserve the voice of De Burgos when transferred into English, simply because she did not write in English. The cultural and historical subtext, as well as the poet's intentions present in the use of Spanish cannot be easily, or at all, replicated, leading us to an impasse. In fact, this is where many scholars might make the extreme statement that poetry is entirely untranslatable.

Emily Apter mentions in an interview about her *Dictionary of Untranslatables*[1] that equivalency between the source and target language is "something on the order of a diplomatic negotiation in which both parties agree to disagree, or something closer to a commercial transaction in which each side calculates gains and losses" (Apter). Perhaps, then, translation is an act of compromise between two languages, with necessary sacrifice on both fronts in order to function. It is a game of tug of war, but not only, as Apter mentioned, between two spheres of language, but between the artful and the technical, or even, perhaps, the

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[1] A large-scale, philosophical work exemplifying the resistance against "easy" translation within cultural, political, and linguistic spheres (Apter).

poet and the translator. It is up to the translator to persist through making these weighty decisions for the sake of circulating poems that deserve a global audience.

Blog Publications and the Francosphere

With the rise of the internet and globalization comes more frequent, more available sources of literature—especially for a shorter form like poetry. This can be seen through an influx of databases and journals, but also less scholarly spaces, such as blog forums that also create a greater number of homes for translated works. While many of these bloggers may not hold much of a scholarly background in translation, the online blog space has opened up doors for greater accessibility within translating. Additionally, many reputable and well-practiced authors/translators log on to these platforms to highlight underrepresented voices. This does not only exist in the Anglophone sphere—in fact, Julia de Burgos's voice can be heard echoing in the Francophone world as well.

      In 2012, French author Edouard Dupas published his French translation of "Río Grande de Loíza" on his blog "Poesie et Racbouni," supposedly the largest Francophone window to the world of global literature. Posting hundreds of poetry translations on the Overblog platform, a well-known European blog for mainstream culture, Dupas utilized an informal space to showcase world literature to a large French audience, which he otherwise might not have been able to do. While no other information could be found about Dupas' credentials, suggesting either a disconnect between French and English literary markets or simply obscurity, it is nonetheless worthwhile to examine one of the only appearances of Julia de Burgos in the French-speaking world.

      As mentioned in Robert N. Sebastian's article "On Translating French Occuring in English into Spanish," structural parallels between Spanish and French such as modifier patterns allows greater ease for translatability in certain cases (Sebastian). This is evident in Dupas' version of "Río Grande de Loíza." In the second line, where De Burgos writes "mi alma se pierda en tus riachuelos," Dupas corresponds with "mon âme se perdre en tes ruisseaux," where in English, it is either "let my soul lose itself in your rivulets," or "let my soul founder in your rivulets" (De Burgos). Here, the Romance language similarities in sound and structure make decisions in word choice much easier for Dupas. Where Agüeros and Schulman must consider the addition of a reflexive, interfering with the flow of syllables, French has the same reflexive "se" as Spanish.

      Another instance where similarity makes translation convenient is in the third line, where De Burgos describes "la fuente," a fountain or a source, and Dupas follows with "la source." In both these words, the double meaning of fountain or spring and source is preserved, while in English, fountain is kept but spring and source are lost. Because French and Spanish have closer roots, De Burgos' voice is more "easily preserved" in cross-language contact. The compromise towards a semblance of the equivalence Apter mentions requires less sacrifice and difficult decision making. However, despite the similarity between the two languages, the voice of the poem still cannot be entirely held together through translation, through the inherent sonic differences, the slight inconsistencies between prepositional meanings, and other structures that separate Spanish from French.

      The argument made here is not against Dupas due to this unorthodox space of publication (generally suggesting amateurishness), but in favor of him, as he grants the Francophone audience what seems to be a thought-out, decisive rendition of a poem that otherwise would not have traveled into that region of the world. With the proliferation of online publishing forums comes the unprecedented ability to globalize

literature, especially compact genres like poetry, through the mixing of scholarly and amateur efforts in translation. As I discuss the global and artistic implications of machine translation services in the next passage, a French machine translation will not be included, as an English one will suffice for the purpose of this paper. However, this step into the Francophone world reveals two things: one, the importance of translation in globalized (English and non-English) literature, and two, that perhaps the most important quality of Dupas' version is the sense of agency and humanism it holds through time spent on diction and interpretation.

Machine Translation

Outside of creating publication spaces such as online blogs, the internet's technological advancements have led to the creation of machine translation services. These generally include three types of models: rule-based, statistical, and hybrid. The first is based directly off dictionary and grammatical rulebooks, the second off statistical models of language usage, while the third is a combination of the previous two (Kadiu). In 2006, Google Translate was launched, using statistical data from legal documents to identify linguistic patterns and use them in the process of translation. Since then, it has developed in grammatical precision and into its 2016 neural machine translation mode, or GNMT, allowing it to examine linguistic contexts and translate full phrases instead of merely working word-for-word. While online translation services such as Dictionary.com, Babelfish, iTranslate, and many others exist, Google Translate has been by far the most commonly used by the international audience.

    The rise of machine translation services has become instrumental to 21st century globalization and naturally, it has led to discussions about the future of translation both inside and far beyond the literary sphere. Can a foreigner visit a city with no linguistic knowledge of the country's native tongue and success at navigating through the streets with merely an online tool? Or, more relevantly to this paper, can these machines make grammatically sensible translations so that full novels are translated without the human touch? Is there some quality that holds them back from replacing the role of translators altogether? Through an assessment and comparison of Google Translate's version of "Río Grande de Loíza," we can get a better sense of an answer to these questions.

    As of right now, the two scholar-translated versions of De Burgos' poem are fighting the machine-translated version for internet visibility. With these blog posts being informal, amateur spaces for circulation of literature, bloggers take less care in finding artful translations that have taken time to consider the poet's language, instead opting for quicker, mechanical services. In fact, digital devices offer an instantaneous web-translation of the Spanish poem upon opening the page. This version is more efficient, less labor-heavy, and cheaper, but can it be considered legitimate?

    Let's say we hold Google Translate and other machine services to the same standards we initially set down for human translators. First, of course, the translation should make sense grammatically. Next, the less discernible condition: the translation should attempt to capture the original poet's essence in the conversion to the target language. With Agüeros and Schulman, we dissected both the metaphorical and syntactical decisions—or, at times, sacrifices—that they made in the process. Could the same be done for these machine-based translations?

    In a side-by-side comparison of the three versions, Google Translate seems to be nearly as grammatically sophisticated as human translators, but it 1) struggles in a few syntactically advanced moments and 2) is unable to pay attention to the

poetics of translation—especially metaphorical context—in the way the scholars did. Despite advancements made in grammatical and syntactical clarity using larger amounts of data to assess greater linguistic patterns, the mechanical translation system still seems to be challenged in a few places inside this poem. The errors made range from benign to fatal in the interpretation of De Burgos' intentions.

First, in line three, the machine translates "para buscar la fuente que te robó de niño" into "to find the source that stole from you as a child." The previously discussed "fuente," or source/spring/fountain re-emerges, and while both human translators opted for the choice of "fountain" for the sake of clarity in imagery, Google Translate chose "source," the more popular translation, instead. While neither diction fully captures the double meaning present in the Spanish and French versions of the poem, the choice of "fountain" prevails over "source," since the absence of the word fountain strips the poem of an initial, concrete image. This not only detracts from the overall flow of the poem from spring water into river, but it also leaves readers confused on a "source" stealing from a child, an instant where the coexistence of abstraction and personification is unproductively ambiguous.

Following line three, Google Translate transforms "y en un ímpetu loco te devolvió al sendero" into "and in a mad rush he returned you to the path." In De Burgos' version, the personified fountain returns the child, though its pronouns are not clarified. The Spanish language is less reliant on personal pronouns—often using only the verb conjugation as an indicator, and this grammatical structure in the poem likely confused the machine, which is not used to moments of personification and a lack of personal pronouns. Thus, it adds "he," interrupting the flow of the line and the intent of De Burgos. Comparatively, neither human translator inserted this additional "he," showcasing the machine's currently inferior grammatical understanding.

Most evidently, however, the machine translation struggles with the final line to a point of obscuring the readers' comprehension of the entire body of the poem. Julia de Burgos ends with poem with great political, emotional, and grammatical complexity:

> " ¡Río Grande de Loíza!... Río Grande. Llanto grande.
> El más grande de todos nuestros llantos isleños,
> si no fuera más grande el que de mí se sale
> por los ojos del alma para mi esclavo pueblo."

She describes the river as a large tear, perhaps the greatest tear of all the islanders except one: her own. De Burgos then utilizes the imperfect subjunctive tense to express her own sorrow—which she deems the greatest of all—in which something flows out of her soul's eyes for her enslaved town or people. Not only is this ending grammatically difficult to comprehend, but it is emotionally charged and perhaps the defining moment that has brought the poem into international fame. Thus, a translation must make sure this significance is communicated as best as possible. Here is a direct comparison of the three endings:

> Río Grande de Loíza!... Great river. Great flood of tears.
> The greatest of all our island's tears
> save those greater that come from the eyes
> of my soul for my enslaved people.

> — Agüeros

> Río Grande de Loíza! ... Great river. Great tear

The greatest of all our island tears,
But for the tears that flow out of me
Through the eyes of my soul for my enslaved people

— Schulman

Río Grande de Loíza!... Big river. Big cry
The greatest of all our island cries,
if it were not greater the one that leaves me
through the eyes of the soul for my slave people.

— Google Translate

Immediately, we notice three large inconsistencies between the human-translated versions and the machine-translated version. First, where the scholars turned "mi esclavo pueblo" into "enslaved people," Google Translate referred to the phrase as "slave people." It even initially had trouble with the adjective placement of "esclavo" and, without a period at the end, translated it into "people slave," an algorithmic error. Of course, there is a difference between "slave" and "enslaved" in this poem, since "slave" is a descriptive adjective, a stagnant state, where "enslaved" is an adjective and a passive participle, with an implied subject of a slaver. The latter is much more empowering, as it ends the poem with a sense of protest that is consistent with De Burgos' implications of the river as a counter to colonial power. Thus, the scholar version makes more sense with the greater political context of the poem.

This is seen again when Agüeros and Schulman reference a "tear" or "our island tears," the machine references "cry" and "our island cries." It is likely that because the algorithm has statistically encountered more direct conversions between "llanto" to "cry" than "llanto" to "tear," it deferred to that. However, since the poem centers on the speaker's relationship with water, it makes much more sense to translate to "tear," since it is a liquid that runs like a river, unlike a cry. This will also provide a better setup for the proceeding line. Thus, it is shown here that despite the fact that it is now able to translate based on grammatical context, the machine is not aware of metaphorical context.

Lastly, the machine translation showcases its own inability to process a line both metaphorically and syntactically advanced such as "si no fuera más grande el que de mí se sale / por los ojos del alma para mi esclavo pueblo." While the human translations have no issue adjusting to this tense by identifying the river as the largest tear "save" or "but" the speaker's own tear—even while the original voice might be slightly diminished—the machine puts out a nonsensical statement: "if it were not greater the one that leaves me through the eyes of the soul for my slave people." While it is able to identify the imperfect subjunctive "fuera" and convert it into "if it were" the machine is simply unable to process the complexly worded meaning behind the line, leading it to create a translation that renders De Burgos' voice into one that is awkward and confounding instead of powerful. The computer-translated version of "Río Grande de Loíza" is largely comprehensible, but it fails to process certain advanced and metaphorical language. This is rooted in the fact that it functions on an algorithm, which is fundamentally both the engine and the drawback of this tool. On one hand, the speed of its statistic-based conversion from language to language is incredibly useful, speeding up the periodicity of translation, but on the other hand, being a machine, it lacks a few elements of humanism that prove beneficial to

translating poetry. This remains the case even with modern developments of Artificial Intelligence, such as ChatGPT—which, despite its greater technological sophistication and grammatical awareness, still slightly falters in precision and, crucially, is still unable to recognize metaphorical context.[2] This, once again, is due to the fact that these machines are engines and algorithms, unable to make true, human decisions.

Using theory to investigate the shortcomings of mechanical translation in a chapter of his book "Human vs Machine Translation," Silvia Kadiu presents Henri Meschonnic's poetics of translating. Meschonnic believed that in translation, theory is inseparable with practice—and, importantly, a translator must make a decision. Kadiu then brings in Jacque Derrida's theory of Undecidability, the impractical condition of human decision-making that constitutes a decision. "A decision is a decision only if it exceeds the application of a rule or law," states Kadiu, reasoning that to forgo a proper translation, the transfer must make a choice beyond calculation. He argues that a machine is unable to enter this state of Undecidability that way scholars are able to, because machines run on statistical and grammatical models created by humans and human experience (Kadiu). Thus, two conclusions are made: 1) if decision-making is fundamental to poetic translation, mechanical translation fails, and 2) humans remain the backbone of machine translation.

Conclusion

This paper set out to question the metrics of success in translation, as well as the machine's ability to meet this margin. The voice of Julia de Burgos was selected because of its colonial resistance, cultural power, and global significance through the context of her homeland, Puerto Rico. With the converse rise of translation and globalization comes the rise of larger readership through both formal and informal multilingual online spaces. As the periodicity of translation increases, the meaning of translation begins to be challenged.

By comparing Agüeros' and Schulman's translations of Julia de Burgos, their attempts to capture the voice both nationally and internationally recognized for its global, emotional, and poetic capacity, we come to understand that the success of translation is difficult to determine. As Adam Czerniaski established in "Translation of Poetry," poetry in translation is something that cannot rely merely on resemblance as a condition of success, since it can be unattainable (Czerniaski). From Agüeros' priority of sticking to grammatical structures and Schulman's decisions to build onto the central metaphor through sacrificing minute, word-for-word details, we learn that syntactical precision and artfulness are both valid approaches to translation—they are, as Czerniaski exemplifies, reproductions of the same portrait using different mediums.

However, certain standards or factors for translation become highlighted in their own absence, seen through machine-translation analysis. From assessing Google Translate's "interpretation" of Río Grande de Loíza, it is shown that

1. As of now, machine translation is still unable to process certain advanced structures in poetry.

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[2] For instance, the 2023 Chat GPT version does not experiment with "undulate" or "elongate" in the first stanza, choosing to remain with the more statistically used and less metaphorically pleasing word "stretch" as seen in Google Translate. Additionally, while it is able to dissect the subjunctive phrase of the final two lines, it also cannot amount "llanto" to tears, instead translating it into "sorrows," an appropriate commonplace choice but less poetically sufficient as compared to the scholar versions.

2. More importantly, machine translation is unable to process metaphorical context in poetry.

Through discussions Kadiu's markers of supportable translation, we establish that

1. Decision-making through the space of Undecidability is crucial to translating literature.
2. Algorithmic translation cannot make these decisions.
3. Humanism is necessary for translation, since human decisions are
    a. The backbone of these statistical systems.
    b. The backbone of poetic translation as we have defined it.

The thought of humanism in Undecidability brings me back to the thought of sacrifice in translation, that compromise made between languages to achieve a semblance of equivalence, as Emily Apter suggested. It brings me back to the concept of struggle. In their respective translations of "Río Grande de Loíza," Agüeros and Schulman struggle with decision-making through the space of Undecidability before coming to their choice on diction based on their interpretations of the poem. Though structural limitations—such as equivocality and non-equivocality—present obstacles for the translator in striving for resemblance to the source text, human translators actually achieve something else through the decisions they make. Through the crossing of two intentions, two voices, two sets of decisions—one, of the poet, the second, of the translator—something new is created. It would be irresponsible to ignore the role machine translation has in the literary future. Algorithmic and neural translation models will continue to develop—especially with growth in the field of artificial intelligence, which, as aforementioned, has the potential to translate even more precisely than machine models—but the standards that we have set (those of true decision-making and metaphor-comprehension) are near impossible for the machines to reach. Still, it is possible that a new set of standards be created for machine translation in the sphere of poetic and literary translation. While humanism will remain crucial, machines might be able to aid in complex comprehensions of the source text, where the voice and intentions of the original poet become visible through comparison. The factor of choice and decision making in word choice can be laid upon the audience, where Undecidability comes alive, allowing translation to engage not only scholars but readers. Through interactive translatability comes greater global and cultural comprehension—where "Río Grande de Loíza" is taught with three translations instead of one, where definition is not stagnant, the sound of De Burgos' river can be heard with greater fluidity.

Translation does, in some ways, equate to loss—Julia de Burgos' voice in English is simply not merely her own, and there will always be an aspect of untranslatability or even misinterpretation due to the structuring of languages. When Spanish turns to French, to English, it becomes something else entirely, a recreation, a mingling of voices. The role of the translator, through the technical, artistic, and sacrificial movements, is not only to preserve, but to create. While only scholars might be able to make the decisions required for "proper" translation, the statistical models that machines are based on may create an entirely different voice. That is to say, there are many directions these new and old forms of translation can be taken, and, in that movement, intrinsically fluid as a river, something global is always gained despite what has been lost.

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Applications of and Challenges to Freud's Oedipus Complex in Hermann Hesse's *Demian*

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Abstract

Demian, a *bildungsroman* by Hermann Hesse, has often been read as a direct application of Jungian theory, but biographical and textual evidence suggest that the novel simultaneously applies and challenges Freud's Oedipus complex. Sinclair initially follows the complex as he, the son, demonstrates ambivalent feelings towards Demian, the father-substitute totem, and expresses his incestuous sexual desires for Eva, the mother. However, as Sinclair successfully pursues Eva instead of finding an outside sexual object to replace her, he diverges from the traditional Oedipal sequence of the *bildungsroman*. Furthermore, Sinclair replaces Demian and continues to inhabit his new Oedipal condition at the end of the novel without "moving on" from the complex as Freud suggested, and his implicit homoromantic desires for Demian defy the heteronormativity that serves as the basis of the Oedipus complex. Unlike a Jungian analysis, which interprets the novel only as a direct application of Jung's individuation process, a Freudian perspective notes Hesse's simultaneous applications of and challenges to the Oedipus complex. From a Freudian lens, the text adds complexity to the protagonist's exploration of identity and enriches the thematic diversity of the *bildungsroman*.

1. Introduction

Demian by Hermann Hesse, published in 1919, is a *bildungsroman*, or "a novel of formation," that portrays Emil Sinclair's psychological growth and transformation as he navigates the complexities of adolescence. As Sinclair transitions into adulthood, he struggles with his identity and searches for a sense of "self," grappling with his inner desires. Ultimately, Sinclair, with the assistance of his mentor Demian, evolves from a confused and vulnerable young boy to an enlightened and self-aware individual who begins to find his path in life. However, it must be noted that while *Demian* is an experimental *bildungsroman* appropriate to the Modernist period, it is unusual in the sense that its central motif is the protagonist's desire to

court his mentor-friend's mother.

Critics disagree on whether Freudian or Jungian theories of psychoanalysis primarily influenced *Demian*. Scholars supporting the Jungian interpretation of the novel have credited Hesse's multiple psychoanalytic sessions with Josef Bernhard Lang, a student of Jung, to argue that Hesse was knowledgeable of Jungian theories of psychoanalysis while writing the novel. According to Osman Durrani, Hesse, deeply traumatized by his wife's psychosis, an opium habit, and a literary impasse, attended therapy with Lang from May 1916 to November 1917 in the hopes of resuming his career (Durrani 903). *Demian*, written between September and October 1917, was published in the spring of 1919.

However, Benjamin Nelson, publishing two newly recovered 1963 letters from Hesse and Jung, offers a different perspective.[1] According to Nelson, Jung claims that he had a direct influence on *Demian* because he knew both Hesse and Lang (B. Nelson 11).[2] Jung furthermore asserts that he indirectly influenced Hesse's later writing of *Siddhartha* and *Steppenwolf* in a tone that Eugene L. Stelzig describes as "co-opting and condescending" (Stelzig 2). Hesse's response, Nelson describes, "hardly bothers to conceal his annoyance with Jung" (B. Nelson 12). Describing Lang as only partly a student of Jung, Hesse writes that Jung's works "did not impress him so much as did Freud's" and that he did not read Jung's books until 1922 (B. Nelson 12). Nelson also notes the prominence of Hesse's friendliness to Freud in Hesse's 1918 essay "Artist and Psychoanalyst" (B. Nelson 13). In the essay, Hesse writes about familiar Freudian concepts of repression and regression and praises Dostoyevsky for predicting the theories of Freud (B. Nelson 13).[3] Nelson, however, does not see a trace of Jung or Lang in its pages (B. Nelson 13).

It is impossible to ignore the apparent influences of Jung's psychoanalytic theories in *Demian* and the compelling argument that Lang's knowledge of Jung's works was transferred to Hesse and demonstrated in the novel. However, in light of Hesse's letter to Maier, I have doubts regarding whether Hesse intended to embed Jung's theories into his novel or was, as Jung claims about *Siddhartha* and *Steppenwolf*, subconsciously influenced by these themes. Furthermore, the letter, as well as his 1918 essay, indicates that Hesse was more knowledgeable about Freud's theories of psychoanalysis at the time of writing the novel, having read Freud's books but not Jung's (B. Nelson 16). Thus, the question that arises is whether a strictly Jungian perspective can do full justice to this novel. An orthodox Jungian view overlooks the "transparent" (Stelzig 3) influences of Freud's mother myth, or the Oedipus complex, in the text. On the other hand, a strict Freudian perspective ignores the apparent Jungian themes of archetypes and individuation and the divergence of Sinclair's story from the traditional Oedipus complex.

In this essay, I argue that *Demian* is a *bildungsroman* that alters the genre by introducing a queer version of Freud's Oedipus complex. Sinclair partially follows the complex as he, the son, initially feels ambivalent towards Demian, the father-substitute totem, and expresses his incestuous sexual desires for Eva, the mother. This characterization of Demian as the father-substitute and Eva as the mother is supported by multiple implications in the novel that Demian has "killed his father" and is now his mother's lover. Sinclair then identifies with Demian, the totem who

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[1] The letters were in reply to Emanuel Maier, who was gathering materials for a proposed doctoral thesis on Hesse's work at New York University.

[2] Jung also asserts that Hesse's familiarity with Gnosticism was due to his influence.

[3] Hesse references Dostoyevsky as a "poet" who came very close to understanding the essential tenets of analytic psychology, intuiting "those roads which Freud and his students would travel" long before them.

becomes his role model, and seems to subsequently complete the Oedipus complex by finding another female sexual object to fulfill his heterosexual desires. Nonetheless, as Sinclair returns to Eva and successfully pursues his desire for her, he manifests an alternative ending to the Oedipus complex. Sinclair replaces Demian, becomes the totem himself, and continues to inhabit the new Oedipal condition at the end of the novel without feeling sentiments of guilt or a sense of "moving on" from the complex, as Freud suggested. Furthermore, Sinclair repeatedly demonstrates implicit homoromantic desires for Demian, which culminate during their kiss in the final scene of the novel, defying the heteronormativity that serves as the basis of the Oedipus complex. From this perspective, Sinclair's emergence into his full self, diverging from the heteronormative, Freudian sequence of the *bildungsroman*, stretches the boundaries of the genre and demonstrates a queer *bildungsroman* of the totem. Not only does a Freudian reading of *Demian* appear more accurate based on Hesse's biographical information, but it also generates more evidence for the novel's innovative nature.

2. Critical Disagreement About Freudian and Jungian Influence

Demian follows the life of Emil Sinclair from childhood to his time as a soldier during the Great War. After growing up in a strictly religious household, Sinclair's initial interaction with his bully, Franz Kromer, exposes him to poverty and crime, setting the stage for Sinclair's internal conflicts. However, Max Demian, a transfer student, mysteriously puts an end to Kromer's bullying and encourages Sinclair to challenge the traditional Christian doctrines of his school. When Sinclair leaves for boarding school, he develops a drinking habit and lets go of his studies, entering a world of darkness and sin. Nonetheless, he meets Beatrice, a young woman who immediately infatuates him, and venerates her image, which leads him to stop drinking and focus on his studies again. Sinclair also begins to paint his dreams and share them with Pistorius, a local organist who introduces him to diverse philosophies and religions. After Sinclair ends his relationship with Pistorius, he comes across Demian in their hometown, and Demian introduces Sinclair to his mother, Frau Eva. Sinclair immediately recognizes that she is the woman he has been seeing in his dreams. While on his deathbed in a military hospital, Demian delivers a kiss to Sinclair, stating that it is from Eva. Sinclair then realizes that he can now see Demian reflected in his inner self.

Hans R. Schmid interprets *Demian* within the framework of Freud's Oedipus complex (Schmid 151). According to Schmid, Sinclair's admiration for Demian, the mirror-image of his complementary self, is basically narcissistic, and Sinclair, arrested at this level of narcissism, is incapable of genuine love for a woman (Schmid 152). Schmid furthermore interprets Sinclair's infatuation with Frau Eva as a regression to narcissism rather than an attempt at liberation from the mother complex (Schmid 156). Additionally, Donald F. Nelson claims that the boyish facial characteristics of Beatrice signify that Sinclair's psychological preoccupation with her amounts to a regression to the homoerotic phase of psychosexual development (D. Nelson 57).

Stelzig notes the Freudian influences in *Demian* as well. [4] According to Stelzig, Sinclair's subconscious yearning for Frau Eva reflects the Oedipus complex, in which the son experiences sexual desire for the mother, transferred from his own mother to Demian's (Stelzig 3). Accordingly, Sinclair is unable to confess his "dark dream of love" about the forbidden embrace of the half-masculine, half-motherly figure even to Pistorius, his mentor, due to the ancient taboo of incest. Even though this repressed desire of the Oedipus complex is never fulfilled, Eva seems to encourage a sexual union between Sinclair and herself, and the desire is completed in Sinclair's dreams, in which, he writes, his "union with her was accomplished by way of allegory."

Some scholars, however, note Jung's theories of psychoanalysis as the dominant influence behind *Demian*. For example, Stelzig describes the novel as "strongly marked by the impact of Jungian analysis," considering its incorporation of various features and tendencies of Jungian thought (Stelzig 1). These aspects include the assumption that the individual is the primary reality, the prophetic language about the challenges and hazards of the individuation process, an amoral attitude to the "dark" suggestions of the self, mysterious connections between the inner and outer worlds, and the endorsement of creative activity as an instrument of self-realization (Stelzig 1).

Johanna Neuer more specifically explores the specific Jungian archetypes, or images embedded in the collective unconscious, that are symbolized within the novel's characters. According to her, Demian possesses multiple projections of the collective unconscious, including the archetypal qualities of the wise old man (sage) as well as the *puer aeternus*, or "eternal boy" (Neuer 10). As the wise old man, Demian is Sinclair's master and teacher, symbolizing the pre-existing meaning hidden behind the chaos of life. This guiding function is also indicated by his name, which, according to Joseph Mileck, is a slightly altered version of *diamōn*, Socrates's guiding spirit (Mileck 171). Demian's simultaneous role as the *puer aeternus*, asserts Neuer, is identified in his timeless beauty, contained in an ageless face, and his unique relationship with his mother that attracts rumors that they are lovers (Neuer 11-12). According to Jung, the consciousness's encounter with subconscious archetypes—in this case, Sinclair's encounter with Demian—is a tremendous ordeal that demands the utmost moral fortitude. Thus, Neuer claims, Sinclair avoids Demian after their first meeting, feeling a sense of guilt for not properly fulfilling his destiny (Neuer 11). However, Sinclair ultimately accepts Demian during his religious celebration of confirmation, which becomes a ritual that signifies his acceptance into the realm of Demian's thoughts, or the absorption of the subconscious into consciousness, symbolizing the beginning of Sinclair's individuation process (Neuer 11).

Stelzig, who more simply interprets Demian as the Jungian shadow, claims that the mounting pressure of his individuation leads Sinclair to find Beatrice as an attempted escape (Stelzig 3). However, when Sinclair paints a portrait of Beatrice from his subconscious, the portrait resembles Demian's face, as well as his "inner self, [his] fate or [his] daimon," and this futile attempt to escape individuation guides Sinclair back to self-realization. Nauer, on the other hand, interprets Beatrice as a symbol of the Jungian anima, the femininity in the male subconscious, due to her youthful looks, anonymity, hermaphroditic quality, and influence on Sinclair to

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[4] While Stelzig's article focuses on the Christian motifs in *Demian*, he describes the novel as "a composite of various influences, or rather confluences." These influences include Jung, whose "note is clearly the dominant one in the composition of *Demian*," the German Romantics, Hegel, Nietzsche, Christianity, Gnosticism, Bachofen, and Freud.

bring his unconscious material into light via drawing (Neuer 12-13).

Another illustration that Sinclair creates from his subconscious is a painting of a bird struggling to hatch out of an egg and flying toward Abraxas. According to Neuer, Abraxas, the symbol of unity between bright and dark, embodies the process of individuation, in which Sinclair's goal is to unite his subconsciousness and consciousness into one personality and emulate the totality of Abraxas (Neuer 13). Stelzig furthermore asserts that the bird flying toward Abraxas represents Sinclair's attempt to complete a rebirth into a new self and head toward the totality of personality (Stelzig 2).

Additionally, Nauer interprets Frau Eva as a symbol of the Jungian Great Mother archetype, the mythical mother of all mankind who is the origin and destination of all mankind (Neuer 13). Sinclair recognizes Eva, Demian's mother, as his ultimate goal after repeatedly seeing her in his dreams, an area heavily influenced by the subconscious. Furthermore, Neuer claims that Eva's character corresponds with Jung's three essential aspects of the archetype: goodness, passion, and darkness (Neuer 15). Her hermaphroditic attribute represents the unity of the psyche, and the name "Eva," which means "life" and "living" in Hebrew, points clearly to her image as the primordial mother (Neuer 15).

Lastly, at the end of the novel, a dying Demian advises Sinclair, "You must hearken to the voice inside you, then you will notice it is I, that I am in you" (206-207). According to Neuer, this guidance implies the completion of Sinclair's individuation; whenever Sinclair is confronted with a problem for which his conscious resources do not suffice, he can reach the forces dwelling within the unconscious of his nature, represented by Demian (Neuer 10, 15). By recognizing Demian's image within himself, Neuer asserts, Sinclair has integrated his subconsciousness into his consciousness, which is precisely what Jung means by individuation (Neuer 15).

Nauer's strictly Jungian interpretation, while providing meaningful explanations regarding Sinclair's individuation and the hidden archetypes in *Demian*, ignores the apparent Oedipal themes behind Sinclair's relationship with Demian and Eva. I agree with Stelzig that the Jungian interpretation of the mother theme as a symbol of rebirth is "safe," while the Freudian mother myth is "transparent" in the text (Stelzig 3). Taking into serious consideration Hesse's letters to Maier, in which he effectively denies Jung's influence on the novel and confirms his familiarity with Freudian ideas, I will interpret the novel from a Freudian lens, which seems to be the more productive perspective. From this lens, not only is the application of Freud's Oedipus complex transparent, but so are the challenges to the complex and the expansion of the *bildungsroman* that Hesse demonstrates through his novel.

3. The Freudian Totem in *Demian*

Interestingly, only Stelzig discusses the Freudian idea of the totem, describing the sparrow-hawk as Abraxas's totem, "whose esoteric function is the uniting of godly and devilish elements" (Stelzig 2). According to Stelzig, Abraxas and his sparrow-hawk totem represent the progressive integration of the "light" and "dark" realms of Sinclair's divided self, which symbolizes the Jungian individuation process (Stelzig 2). While this interpretation is true in the sense that a totem has spiritual significance, it is not supported by Freudian theory. Upon a thorough understanding of Freud's conceptions of totems and taboos, as well as a deeper reading of *Demian* through an Oedipal lens, the totem in the novel is identified as Demian.

In *Totem and Taboo*, Freud defines a tribal totem as an "object of veneration of a group of men and women who take their name from the totem and consider themselves consanguineous offspring of a common ancestor, and who are firmly associated with each other through common obligations towards each other as well as by the belief in their totem" (Freud 50). A totem "protects and warns the members of the tribe" as well as "foretells the future to those faithful to it and serves as their leader" (49). Freud uses the phrase totem with two meanings: the animal and the group which it represents.

Freud traces the origin of the totem animal to the Oedipus complex: "Psychoanalysis has revealed to us that the totem animal is really a substitute for the father, and this really explains the contradiction that it is usually forbidden to kill the totem animal, that the killing of it results in a holiday and that the animal is killed and yet mourned" (66). According to the Darwinian conception of the primal horde, he claims, there was originally "only a violent, jealous father who keeps all the females for himself and drives away the growing sons" (66). Then, one day, "the expelled brothers joined forces, slew and ate the father, and thus put an end to the father horde" (67). There remained, however, an ambivalent feeling, both love and hatred, toward the father among the sons:

> They hated the father who stood so powerfully in the way of their sexual demands and their desire for power, but they also loved and admired him… After they had satisfied their hate by his removal and had carried out their wish for identification with him, the suppressed tender impulses had to assert themselves. This took place in the form of remorse, a sense of guilt was formed. (67)

This guilt led to the creation of the totem as a substitute for the father: "They undid their deed by declaring that the killing of the father substitute, the totem, was not allowed, and renounced the fruits of their deed by denying themselves the liberated women" (67). Thus, the sons "created the two fundamental taboos of totemism" (67), prohibitions against killing the totem (animal) and having sex within the totem (group). "[For] this very reason these had to correspond with the two repressed wishes of the Oedipus complex" (67), the desire to murder the father and the sexual desire for the mother.

Multiple instances in *Demian* imply that Demian has killed his father and has replaced his father as his mother's lover. For example, Sinclair repeatedly describes Demian's relationship with Eva, his mother, as intimate: "No one liked him, he was intimate with no one, except his mother, and his relations with her did not seem like those of a child, but those of a grown-up person" (59). As a relationship between two grown-up people has sexual implications, Sinclair implicitly indicates that Demian is engaged in a sexual relationship with Eva. Demian, however, does not mention Eva frequently to Sinclair during the novel's early chapters: "He seemed to live on very intimate terms with her, but he never spoke about her, never invited me to his house" (70). Sinclair is not alone in believing that Demian is in an incestuous relationship with his mother. There are widespread rumors that Demian is Eva's lover: "In this connexion [sic] I remember having heard that he was suspected of being his mother's lover" (57).[5]

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[5] This translation is W. J. Strachan's. The N. H. Priday translation, which I reference in the rest of this essay, translates this part as "he was suspected of living with his mother as a mistress." While the two translations convey the same meaning, I find the word "lover" more directly implicational to the Oedipus complex than "mistress."

Furthermore, Demian is repeatedly described as strong and, in one instance, mentions murder as a solution to Franz Kromer's repeated harassment against Sinclair: "'All right,' Max Demian said, smilingly. 'Go home now! We will put things square, although murder would have been the simplest. In such matters the simplest way is always the best'" (48). This suggestion to kill Kromer implies that Demian believes the murder of his enemies is justified. The strong Oedipal situation in the text implies that this group of enemies, at one point, included his father. According to the Oedipus complex, all sons subconsciously desire to murder their father, but the taboo originating from the primordial murder of the father suppresses this impulse. Demian, however, seems to be skeptical, even scornful, of conforming to such taboos when he says, "Whoever is too lazy to think for himself and to constitute himself his own judge simply conforms to the taboos, whatever they happen to be" (77). Thus, the text implies that Demian has rejected the two taboos that Freud points out, the taboos against the murder of the father-substitute and against incest, and has manifested his Oedipal desires by murdering his father and engaging in intimate relations with his mother.

Freud additionally discusses how the totem animal is taboo, referencing Émile Durkheim: "Durkheim has shown in his writings how the taboo, which is attached to the totem, must have entailed the prohibition against putting a woman of the same totem to sexual uses" (57). Taboo is a Polynesian word that has a double meaning: "[on] the one hand it means to us sacred, consecrated: but on the other hand it means, uncanny, dangerous, forbidden, and unclean" (13). Freud also describes these mixed feelings, which stem from the simultaneous admiration and animosity for the father in the Oedipal complex, as "awe and aversion" (17) and "tenderness and hostility" (33). Taboo individuals are venerated as well as feared, guarded as well as guarded against.

The ambivalent feeling that the son feels towards the father is evident in *Demian*. When Sinclair enters the novel's Oedipal triangle as the allegorical son of Demian and Eva, he demonstrates this taboo sentiment, or "awe and aversion," towards Demian, his father-substitute totem. For example, after Demian mysteriously talks to Kromer, Sinclair's bully, convincing him to stop bullying Sinclair, Sinclair describes his mixed feelings towards Demian: "The old, embarrassed feeling concerning him came over me—an odd mixture of gratitude and shyness, of admiration and fear, of affection and inward resistance" (50). This ambivalent sentiment towards Demian highlights his taboo quality. Sinclair recognizes this quality not only in Demian's personality, but also in his looks: "Perhaps he was beautiful, perhaps he pleased me, perhaps even he was repugnant— I could not then determine" (61). Again, Demian is characterized with concurrent descriptions as admirable and distasteful, emphasizing his position as Sinclair's totem. This sentiment follows Sinclair to his boarding school, where he is physically separated from Demian: "I had often a great longing for Max Demian; on the other hand, I hated him not seldom, and looked upon him as responsible for the moral impoverishment of my life" (84). As Sinclair blames Demian for his "moral impoverishment" yet longs for him at the same time, he continues to demonstrate ambivalent feelings towards his totem Demian.

Freud furthermore asserts that the taboo has a "capacity of displacement," or "transference," in which "[anyone] who has violated a taboo by touching something which is taboo becomes taboo himself" (18). This phenomenon, he claims, is because the individual who has violated a taboo "has the dangerous property of tempting others to follow his example" (20). According to him, the "basis of taboo is a forbidden action for which there exists a strong inclination in the unconscious" (20). In the case of the Oedipus complex, these forbidden actions are

the murder of the father, substituted by the totem animal, and sexual relations with other female members of the totem group.

When Sinclair asks Demian whether following his subconscious desires justifies committing "actually forbidden" (Hesse 76) actions, including murder and rape, Demian primarily encourages Sinclair to decide what is "really 'taboo'" for himself:

> But you haven't yet reached that point where one can see what is 'permitted' and what is really 'taboo.' You have realized only a part of the truth. The remainder will come after, rely on it. For instance, for the past year or so you have had in you an instinct which is stronger than all the others, and which is held to be 'taboo.' (76)

As Demian denounces society's arbitrary taboos, he encourages Sinclair to defy society's expectations to conform to such definitions. Demian has repeatedly challenged the dominant Christian ideologies, which he is expected to follow, claiming that "Cain was a thundering good fellow, and this story [of Cain and Abel] got attached to his name simply because people were afraid of him" (34) and that the unrepentant thief on the cross is "a real fellow with plenty of character" (73). According to Demian, "[whoever] is too lazy to think for himself and to constitute himself his own judge simply conforms to the taboos, whatever they happen to be" (77). While Sinclair initially describes these ideas as "blasphemous and infamous" (35) and describes Demian as "different, inconceivably different from us all" (61), he ultimately acquires Demian's taboo. This transference occurs during their confirmation: "It was not into the church that I was ready to be received but into something else, into an order of ideas and of personalities which surely existed somewhere or other on earth, and of which I felt my friend was the representative or messenger" (78). Sinclair's religious celebration of confirmation, which, in most cases, signifies submission to religion and conformity, instead becomes a ritual that represents his acceptance into the realm of Demian's "order of ideas and of personalities," a forbidden—or taboo—order. This displacement of taboo serves as the basis for Sinclair's concern about his "moral impoverishment" (84) as Sinclair now follows Demian's example in challenging the Zeitgeist of the status quo defined by Christianity.

4. Sinclair as the Totem

Sinclair, defying society's expectations to resist "a forbidden action for which there exists a strong inclination in the unconscious" (Freud 20), recognizes his subconscious desire to court Eva, the mother. This desire primarily arises in his dreams:

> This dream, the most important and the most enduring of my life, was as follows: I returned home—over the front door shone the crest with the yellow bird on the blue ground—my mother came to meet me—but as I entered and wished to embrace her, it was not she, but a shape I had never before seen, tall and powerful, resembling Max Demian and my painting, yet different, and quite womanly in spite of its size. This figure drew me towards it, and held me in a quivering, passionate embrace. Rapture and horror were mixed, the embrace was a sort of divine worship, and yet a crime as well. Too much of the memory of my mother, too much of the

memory of Max Demian was contained in the form which embraced me. (117)

While Sinclair has not met Eva yet, the dream figure's resemblance to Demian makes it clear to us that she is Demian's mother, and the simultaneous sentiments of "rapture and horror" that Sinclair feels emphasize the forbidden yet subconsciously alluring nature of incest. Due to the prevalence of incest taboo, Sinclair does not share his "dark love-dream" (137) with anyone, even his mentor Pistorious:

> Of all my dreams, the dark love-dream recurred most frequently. Often, often have I dreamed of it; often I stepped under the crest with the bird on it into our house, and wished to draw my mother to me, but instead of her I found I was embracing the tall, manly, half-motherly woman, of whom I was afraid, and yet to whom I was drawn by a most ardent desire. And I could never relate this dream to my friend. (137)

Again, Sinclair feels a strong incestuous desire not for his biological mother, but for the woman who resembles Demian and embodies masculine qualities. The frequency of this dream highlights the strong subconscious inclination that Sinclair feels for this woman.[6] After Sinclair learns from a photograph that the woman in his dream is Demian's mother, he reunites with Demian and meets Eva. Eva recognizes Sinclair at once, inviting him to call her Mother Eve, a name referred to her only by "very few, very close friends" (178). After their meeting, Sinclair visits Eva and Demian on a daily basis: "From this day on I went in and out of the house like a son and a brother, but also like a lover" (179). Subsequently, Sinclair and Eva's relationship grows stronger. At one point, she confronts him about his love for her and tells him that love "must have the force to be absolutely certain of itself" (186), encouraging a sexual union between Sinclair and herself. Sinclair's Oedipal desire is ultimately completed in his dream, in which his "union with her was accomplished by way of allegory" (189).

At the end of the novel, Sinclair replaces Demian as the father-substitute totem. When Demian dies during the Great War, he gives Sinclair a kiss from Eva: "'Mother Eve said that if ever you were ill I was to give you a kiss from her, which she gave me... Close your eyes, Sinclair!' I obediently closed my eyes. I felt a light kiss on my lips" (207). As Demian delivers a kiss from Eva to Sinclair, he effectively transfers his own sexual relationship with Eva to Sinclair. Now, Sinclair replaces Demian, who once became the totem as the substitute for his own father. It is important to note that, while Sinclair, the son, replaces Demian, the father-totem, he does so in a nonviolent manner without realizing his desire to kill the father.

According to the novel's last lines, Sinclair can now find Demian in the depths of his soul after Demian's death:

> But my soul is like a mysterious, locked house. And when I find the key and step right down into myself, to where the pictures painted by my destiny seem reflected on the dark mirror of my soul, then I need only stoop towards the black mirror and see my own picture, which now completely resembles Him, my guide and friend. (207)

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[6] Freud, in *The Interpretation of Dreams*, claims that the dream is "a perfectly valid psychic phenomenon, actually a wish-fulfilment" (44) that carries out subconscious desires in a disguised way. From a Freudian perspective, Sinclair's "dark love-dream" emphasizes the heavy presence of his Oedipal, incestuous desire for Eva in his subconsciousness.

Sinclair can now identify Demian in himself, whose mirror image "completely resembles" Demian. According to Freud's resolution of the Oedipus complex, the son ultimately identifies with the father, internalizing his values and perceiving him as a role model rather than a rival. Accordingly, Sinclair identifies with Demian, who is now his role model, and stops feeling ambivalent sentiments towards him. Furthermore, Demian's incest taboo has been completely transferred to Sinclair through the kiss from Eva, and Sinclair now assumes Demian's role as the father-substitute totem who has manifested his incestuous desire for the mother. Again, it is important to note that the other Oedipal desire, the desire to murder the father, has not been manifested in the novel's ending. Demian has peacefully left the position of the father due to an external reason. Through the kiss, he has, in a way, passed the torch to Sinclair, and Sinclair still calls him a "friend" without any sentiments of guilt about his death. Meanwhile, Sinclair is left in the Oedipal triangle without "moving on" from the complex as Freud suggests.

5. Challenges to the Oedipus Complex and the Expansion of the *Bildungsroman* in *Demian*

While Hesse adheres to certain aspects of Freud's Oedipus complex throughout *Demian*, he offers significant challenges to the complex in crucial parts of the text. For example, Sinclair does not continue pursuing Beatrice, the outside sexual figure who, according to Freud, would serve as a substitute for his sexual desire for Eva, the mother. After drawing an image of Beatrice from his subconsciousness, inspired by a young girl he meets at the park, Sinclair is initially enamored with her image: "the impression was deeper than all the former ones, and the influence of this infatuation on my life was powerful" (97). Seeming to reflect Freud's idea that a sexual desire for an outside woman replaces the son's desire for the mother, Sinclair even describes his noble pursuit for Beatrice as "not the action of flying back or crawling back to mother" (98). However, his desire for Beatrice only leads him back to his Freudian incestuous desire for Eva, his allegorical mother. Meanwhile, Sinclair's desire for Beatrice slowly recedes from his center of attention: "The figure of Beatrice, which had for a certain time occupied so much of my attention, vanished by degrees from my mind, or rather receded slowly, drawing nearer and nearer to the horizon, becoming darker, more like a shadow, as it retreated. She satisfied my soul no longer" (116). Sinclair realizes that Beatrice, the outside sexual figure, does not satisfy his soul, and a new "longing for a full life" (116) glows in him. His desire for Beatrice, which, according to Freud, should satisfyingly substitute his incestuous desire for the mother and lead him to the resolution of his Oedipus complex, does not lead to a "full life." Thus, the text directly contradicts Freud's idea that moving on from the Oedipus complex, through an identification with the father and the discovery of desires for other women, leads to the development of an individual.

In fact, it is the incestuous desire for Eva that replaces the desire for Beatrice in Sinclair's dark love-dream:

> A certain dream, or play of fantasy, which occurred to me, was full of significance. This dream, the most important and the most enduring of my life, was as follows: I returned home––over the front door shone the crest with the yellow bird on the blue ground––my mother came to meet me–– but as I entered and wished to embrace her, it was not she, but a shape I had never before seen, tall and powerful, resembling Max Demian and my painting, yet different, and quite womanly in spite of its size. (116-117)

Instead of turning to an outside sexual figure to replace the mother and resolve the Oedipus complex, Sinclair defies Freudian theory by continuing to pursue Eva, the mother, and even finding success in his pursuit.

Hesse additionally challenges Freud's Oedipus complex by leaving Sinclair in his Oedipal triangle at the end of the novel. According to Freud, the son ultimately identifies with his father, internalizing his values and behaviors, and finds an outside sexual figure to direct his desires, moving past the complex and emerging into his full self. In the conclusion of *Demian*, Sinclair does identify with Demian, the father-substitute, seeing him reflected in the mirror of his soul. However, we do not see him moving past the Oedipus complex to become his complete self. Instead, Sinclair finds himself in a different Oedipal condition, in which he is now the father and the totem, and he has emerged into his full self in this Oedipal triangle. He never leaves the Oedipal complex—remaining a child, in a way. From a strictly Freudian perspective, Sinclair's journey is a failed *bildungsroman* as he does not progress past his Oedipal situation. However, under Hesse's queer version of the Oedipus complex, Sinclair is able to emerge into his full self without moving beyond his Oedipal triangle.

Furthermore, as we return to Freud's idea about the origin of the totem, it must be noted that Sinclair replaces his allegorical father in a nonviolent way, contradictory to Freud's theory. While Sinclair does realize his sexual desire for the mother by replacing the father, Demian's death at the end of the novel is not a manifestation of Sinclair's desire to murder the father. Instead, Demian dies in the Great War, a circumstance beyond Sinclair's control, and Sinclair finishes his story describing Demian as "[his] guide and friend" (207). Sinclair never demonstrates his Freudian desire to murder the father, contradicting Freud's claim that this subconscious desire exists in every son. Demian's nonchalance with Sinclair's pursuit of Eva further supports this seemingly peaceful transition of power. Demian, in fact, encourages Sinclair's pursuit, telling Sinclair that Eva knows of him (167) and inviting Sinclair to his home (171). He also transfers his Oedipal relationship with Eva to Sinclair when he delivers a kiss from her to Sinclair moments before his death. This behavior defies the Freudian origin story of the totem, in which the sons aggressively take the females from the violent, jealous father who keeps all the females for himself.

Moreover, it is impossible to ignore the homoerotic undertone in the relationship between Sinclair and Demian. When Sinclair discusses Demian's appearance, he describes him as "beautiful" and pleasing: "Perhaps he was beautiful, perhaps he pleased me, perhaps even he was repugnant—I could not then determine" (61). While this description, from a Freudian perspective, exemplifies the taboo feelings, the "awe and aversion," that Sinclair feels for Demian, it also expresses Sinclair's implicit homosexual desire for Demian. During the period of this novel, Paragraph 175 of the German Criminal Code outlawed homosexuality in Germany (Huneke 52). Taking this ban into consideration, Sinclair feels ambivalent toward Demian due to the German Zeitgeist regarding homosexuality during his time, which influenced him to find Demian "repugnant" despite his attraction toward him.

Eva's resemblance to Demian must also be noted in the discussion of the implicit queer relationship between Sinclair and Demian. When Sinclair initially describes his "dark love-dream" with Eva, he recognizes her resemblance to Demian: "Too much of the memory of my mother, too much of the memory of Max Demian was contained in the form which embraced me" (117). Considering his description of Demian as "beautiful" and pleasing, it is not surprising that Sinclair is strongly attracted to Eva, who embodies "the memory of Max Demian." From this queer perspective, Sinclair turns to Eva as a replacement for Demian, whom the status quo

forbids him from sexually engaging with.

This queer undertone between Sinclair and Demian culminates in their kiss at the end of the novel: "'Mother Eve said that if ever you were ill I was to give you a kiss from her, which she gave me... Close your eyes, Sinclair!' I obediently closed my eyes. I felt a light kiss on my lips" (207). From a strictly Freudian perspective, this kiss represents the transfer of taboo from Demian to Sinclair. However, in light of the implicit queer relationship between the two characters, the kiss represents the final expression of the sexual desire between Sinclair and Demian, who reciprocates Sinclair's desire. Sinclair emerges into his true self through this kiss, which allows him to demonstrate his repressed desires.

By challenging elements of Freudian theory and introducing homoerotic elements in *Demian*, Hesse effectively expands the genre of *bildungsroman*. Many modern *bildungsroman*, most notably *Sons and Lovers* by D. H. Lawrence (Gillins 274), engage with Freudian theory by directly applying the Oedipus complex. In these novels, the protagonists experience and "move on" from the Oedipus complex to emerge into their complete selves. However, by applying a queered version of the Oedipus complex to Sinclair's novel of formation, where the protagonist continues his pursuit of the mother, maintains an amicable relationship with the father, and remains in the Oedipal triangle at the end of the novel, Hesse opens new doors that enrich the genre of *bildungsroman*. Furthermore, most modern *bildungsroman*, including works based on the Oedipus complex, typically illustrate their protagonists' growth and formation in a heterosexual context, while Hesse integrates an implicit homosexual relationship in Sinclair's journey of formation. Adding complexity to the protagonist's exploration of identity and self-discovery, Hesse successfully enriches the thematic diversity of the *bildungsroman*.

6. Next Steps in the Scholarship of Hesse, Freud, and the *Bildungsroman*

While a Jungian analysis of *Demian* produces a useful interpretation of the text, a Freudian perspective approaches the text as a *bildungsroman*, offering a robust interpretation of the novel that we do not see from Jungian analysis. As I have demonstrated, Hesse both applies and challenges Freud's Oedipus complex in the text, and this Freudian understanding establishes the novel as a genre-buster that pushes the *bildungsroman* forward by breaking conventional expectations.

Considering this Freudian interpretation, critics of Hesse should now turn their attention to the applications and challenges of Freud's theories in other texts by Hesse. I have corroborated Hesse's claims that he was well-acquainted with Freudian ideas before the writing of his major novels: *Demian* (1919), *Siddhartha* (1922), *Steppenwolf* (1927), and *Narcissus and Goldmund* (1930). Not only did he apply Freud's theories, but he also *queered* them, demonstrating a rich understanding of Freud's works. Instead of attempting to understand his works from a strictly Jungian or Freudian perspective, scholars must now offer interpretations of Hesse's works in light of his ability to *queer* psychoanalytical theories, which is not limited to the Oedipus complex. These interpretations will allow us to understand Hesse's nuanced way of storytelling more thoroughly.

Furthermore, Freudian scholars should now identify the variations of Freudian theory, particularly the Oedipus complex, in modern *bildungsroman*. Although Freud claimed that his theories accurately described the transition from adolescence to adulthood, many writers of *bildungsroman* have challenged his ideas.

For example, Hesse, as I have demonstrated, both applied and challenged Freud's theory in his literature, revealing where his literary vision converges with and diverges from the Freudian conception of the *bildungsroman*. Freudian scholars should not stop at recognizing the direct manifestations and antitheses of Freudian theory in literary works. They should furthermore interpret more literary works as nuanced applications, or challenges, of Freudian theory, offering a richer understanding of the psychoanalyst's influences in the literary world.

Finally, I have demonstrated that Hesse effectively expands the genre of *bildungsroman* through his queering of the Oedipus complex and his integration of homoerotic undertones into Sinclair's novel of formation. Literary scholars addressing the *bildungsroman* as a novelistic genre should now investigate the history of the *bildungsroman* in relation to how authors have challenged the status quo to expand the genre. Noting the efforts of writers to provide more diverse and nuanced explorations of identity and self-discovery, scholars should provide deeper insight into the genre's history of expansion and recognize the expanded genre for what it is.

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Environmental Support Around the World: To What Extent Are Age and Birth Cohort a Factor in Determining Attitudes Towards Environmental Protection?

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1. Introduction

The recent declaration of "the era of global boiling" by UN Secretary-General António Guterres confirms that the effects of climate change and environmental degradation are more prominent than ever before. While limiting global temperature rise to 1.5 ℃ may still be possible, even this ambitious aim can only be achieved with "dramatic, immediate climate action" (Niranjan, 2023). Fortunately, there has been a growing number of environmental movements and organizations aimed at protesting against inefficient governmental action and raising awareness about climate action. For instance, the Global Climate Strike Week in September 2019 which took place in more than 150 countries and involved 4 million people (Euronews Green, 2023) was first inspired by 15-year-old Greta Thunburg's Fridays for Future school strikes. The first Earth Day on 22 April 1970 had 20 million people joining to voice their opinions against environmental destruction in the United States, most protests being in college campuses and high schools with passionate students protesting for a greener future (Johnson and Schwadel, 2019) (Yeo, 2023). It is now an important global movement with more than 1 billion annual participants contributing to clean-ups, nature walks, and protests (Young, 2021).

What is particularly interesting about these actions is the active involvement of youth. It seems as though many powerful and wide-reaching environmental movements often involve students and young adults. This brings about an intriguing question on whether age, or perhaps one's birth cohort (more commonly referred to as one's generation), affects the individuals' views towards environmental conservation and action. With the most crucial steps to urgent and effective action being public awareness and attitudes towards environmental issues, understanding the effect of age or generation on an individual's likelihood to value the environment is imperative to target and support specific social groups and encourage environmental action.

Previous studies have already explored this topic, yet most were only able to utilize state-wide or nationwide data to evaluate the effects of age due to the limited availability of worldwide time-series data. Hence, this exploration aims to take advantage of cross-cultural time-series data from the World Values Survey to

determine whether age or generation affects an individual's perspective on environmental protection and to what extent this effect holds across time.

2. Literature Review

There has been increasing scholarly interest in the relationship between age, cohort, and periods with pro-environmental attitudes of the public. Famously, a multivariate study by Frederick H. Buttel (F. H. Buttel, 1987) aimed to evaluate the effects of age and cohorts on environmental values in comparison to previous studies (Buttel and Flinn, 1976) that explored other effects such as socioeconomic class, place of residence (Buttel and Flinn, 1974; Dillman and Christenson, 1972; McEvoy, 1972), and political liberalism (Dunlap, 1975; Costantini and Hanf, 1972; Buttel and Flinn, 1976). Buttel used a statewide survey conducted by the Wisconsin Survey Research Laboratory with 548 respondents in 1974, observing two indicators: environmental awareness and support for environmental protection. Using a zero-order correlation matrix, he observed that both environmental variables primarily displayed an indirect relationship with age, with the youngest showing the most support. It was also suggested that environmental attitudes were more strongly related to age than education or liberalism, concluding that age seems to be the "most consistent predictor" of environmental support. However, it was acknowledged that the inability to differentiate between cohort effects and age group effects was an obvious limitation of the research method, which is what this paper also acknowledges and tries to overcome.

Paul Mohai and Ben W. Twight (Mohai and Twight, 1987) expanded upon Buttel's study by widening the data sample range from the previously used state-specific survey to a nationwide survey conducted by Louis Harris in 1979. In a survey consisting of 7,010 interviewees, variables such as attitudes towards the environment and natural resources, government, and level of citizen activism were explored. Their conclusions largely supported that of Buttel's with statistically significant results, although the study additionally found a difference between environmental concern and activism, reporting that while the younger population expressed the greatest concern, the middle-aged group was the most politically active. This suggests that results may vary depending on the variable used to evaluate environmental attitudes. There was also an attempt to separate aging and cohort effects. Although a simple observation of data failed to disclose a clear difference, Mohai and Twight postulated that cohort effects were more likely than aging effects.

Moving outside of the United States, a larger study was conducted in Europe by Joni Hersch and W. Kip Viscusi using a pool of data from the 1999 Eurobarometer survey (Hersch and Viscusi, 2005). An individual's concern for the environment was determined by their willingness to pay more, specifically for gasoline, to help preserve the environment. With other socioeconomic variables such as sex, marital status, education, and income accounted for, results suggested clear age-related differences, with older age groups much less willing to pay more. The authors attributed this age effect to the difference in environmental awareness and perception of long-term personal benefits of environmental protection policies between the younger and older age groups.

In addition, a similar study by Benno Torgler, María A. García Valiñas, and Alison Macintyre used the European Values Survey (EVS) from 1999-2000 across 33 Western and Eastern European countries to observe the impact of demographic factors such as age, gender, and parental attitudes on environmental concerns. Age here was used as a categorical instead of a numeric variable and dependent variables

used to measure environmental concern included willingness to pay higher taxes, involvement in voluntary organizations, and justifiability of littering. Overall, there seemed to be a negative correlation between age and environmental preferences, consistent with previously mentioned studies. However, a unique feature of this study is the exploration of social norms ("environmental morale"), which showed a positive relationship with age.

For a more recent, large-scale analysis, Brenton M. Wiernik, Deniz S. Ones, and Stephan Dilchert performed a meta-analysis of 68 different primary sources that presented data from 220 independent samples (Wiernik et al. 2012). In an attempt to find the relationship between age and environmental sustainability, variables such as environmental concern, values, awareness, and pro-environmental behaviors were examined. Unlike the previous studies, this report concluded small or negligible relationships between age and all variables mentioned above. The only exception was the pro-environmental behaviors, which, only when further categorized into more specific types of actions saw a direct relationship between age and tendency for active ecosystem preservation and outdoor activity.

Another recent and relevant study by Gray et al. (2019) yielded similar results. The researchers explored whether age or generation (cohort-level measures) has an impact on concerns about environmental degradation, and if not, which other factors impacted one's tendency to worry about environmental health. In order to do so, the researchers collected data from 500 US citizens in an internet survey, then divided birth cohorts into four distinct generations ("The Silent Generation," "Baby Boomers," "Generation X," and "Millennials") to compare with environmental attitudes. Conclusions demonstrated that neither age nor generation had a significant impact on the individual's perception of the severity of environmental degradation issues. Instead, value orientations and political leanings seemed to be a more robust predictor of environmental concern. This demonstrates once again the importance of taking into account other demographic and individual variables even when exploring age and generation effects.

3. Hypothesis

In this paper, the hypothesis is that age and care for environmental protection have an inverse relationship, meaning older individuals are less likely to care about environmental conservation than younger individuals at a given period.

There are multiple theoretical explanations of this relationship, one of which is the idea of temporal discounting. The effect of temporal discounting, the tendency for individuals to "prefer immediate gains at the expense of future outcomes" (Ruggeri et al., 2022), could be a possible reason for the decrease in environmental support at older ages. The nature of environmental problems, such as climate change, requires a "trade-off between short-term and long-term benefits," (Markman, 2018) where the short-term benefits of comfort, profit, or ease often compete against the long-term benefits of ecological stability, cost-savings, and sustainability. Although temporal discounting was found to be a cross-cultural phenomenon (Ruggeri et al., 2022), it seems possible that within populations, younger people have a lower tendency to discount the future because they have a longer future ahead of them compared to older people. Younger people, and perhaps even their progeny, would have to endure the catastrophic consequences of environmental degradation for much longer than older individuals. In contrast, older people may tend to have a mindset that they will not have to endure the future consequences (or, conversely, that they would not be alive to enjoy the potential

benefits of mitigating climate change), and thus could have a high chance of prioritizing the present over the future.

4. Methodology

The dataset that was used for the exploratory analysis was the World Values Survey (WVS). The WVS is a comparative cross-cultural study of social, religious, political, economic, and cultural values of people that aims to assess the change or stability of important values over time. The project was founded in 1981 by Professor Ronald Inglehart and since has published seven different waves of study, representing over 120 countries (World Values Survey Association, 2020). In this paper, WVS wave 7 (2017-2022) and WVS time-series (1981-2022), a collection of all 7 WVS waves, were used in order to observe the attitudes towards environmental conservation both at a single time period across countries and over an extended time period.

The key variable used in this exploration to determine values toward environmental conservation was the "Environment vs. Economy" variable. This variable was chosen because it was tracked in 5 consecutive WVS waves starting from wave 3 (although minimal data was available in wave 4 (1999-2004)) and could provide insight into how much people value environmental protection. In all waves, the question asked respondents to explicitly choose a preference between protecting the environment "even if it causes slower economic growth" versus "economic growth and creating jobs" despite possible environmental consequences (WVS7).

However, it is important to note the limitations of using this particular variable. As Klineberg et al. (1998) mention, the structure of the "Environment vs. Economy" variable itself requires the respondent to consider a trade-off in their decision, that is, choosing the environment at the expense of slower economic growth and limited employment opportunities. Hence, in reality, this variable is not purely measuring the individual's perspective towards environmental protection, but rather their environmental concern "in explicit relation to [another] important consideration" (Klineberg et al., 1998). Moreover, with different age groups having access to different levels of income, the emphasis on economic development may vary due to these differences in financial status, also affecting the results on environmental values. This brings up another key limitation, which is the strong influence of periodic effects on the respondents' preferences. For instance, during times of global economic instability such as the Great Depression, the 2008-2009 Financial Crisis, or even the COVID-19 pandemic[1], it is highly likely that people will prioritize the economy over the environment.

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[1] The COVID-19 pandemic might be an unusual exception due to the nature of this economic crisis. Although economic instability was indeed a major issue, it is also notable that environmental awareness was heightened due to massive health concerns during the pandemic. A survey conducted by Boston Consulting Group identified that around 70% of survey participants were more aware that anthropogenic activity directly impacts environmental degradation, and in turn also affects societal well-being and health (Kachaner, 2020).

5. Results & Discussion

WVS Wave 7

In order to begin exploring the impact of age on environmental concerns, it is important to determine whether there is even a difference of opinion on environmental conservation across age groups. The WVS wave 7 data could be utilized to create an individual-level visualization illustrating the number of people valuing the economy versus the environment in each age group.
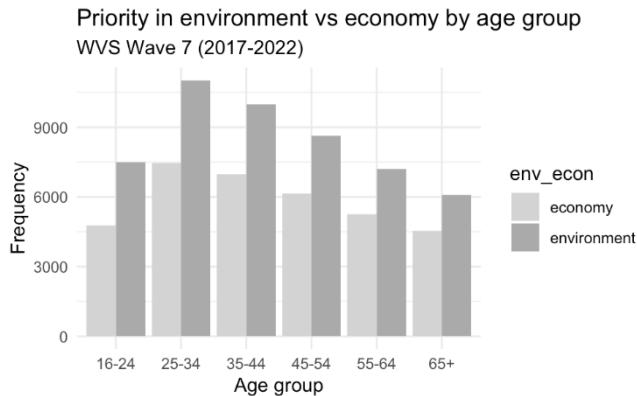
Figure 1. *Priority in given value type by age groups among all individuals surveyed in WVS wave 7 (2017-2022)*

The difference between the frequency of people favoring the environment and the number favoring the economy can be observed to discern which age group has a higher tendency to value the environment over the economy. There does seem to be a clear difference across age groups with the proportion of people in favor of environmental protection decreasing as the age increases from 25-34 years old to 65 years old and above. The greatest difference occurs in the 25-34 age group, where people favoring the environment outweigh people prioritizing the economy by over 3,000 people, or by around 46%. In comparison to the oldest age group at 65+ years old, where only 1,500 more people value environmental protection over the economy, the younger populations seem to have a much greater tendency to support environmental conservation. Even the youngest age group at 16-24 years old has a greater proportion valuing the environment than the two oldest groups. This could suggest that between 2017-2022, age does seem to have a positive impact on an individual's likelihood to care for the environment.

However, at this stage, it is difficult to discern between age (or lifecycle) effects and generational (or birth-cohort) effects. At a single point in time, the age effects and generational effects are indistinguishable from each other because all individuals born in a particular year would be of the same age at the same time. The effect seen above could be a universal age effect, that there is a tendency for an individual to value the environment less as they age. This means that regardless of generation or time of survey, the older age groups will always have a smaller proportion that favors the environment, and as time passes, the younger groups will eventually grow older and lean to favor the environment less as well. On the other

hand, the result could also be due to a generational effect, where a certain generation as a whole values the environment more than other generations because of their shared experiences. Over time, this could result in generational replacement as the individuals in earlier generations grow older and pass away and the values of the younger generation take over. This difference will need to be observed using the WVS time series data.

In addition to individual-level analysis, it was interesting to explore whether country-level aggregations demonstrated the same trend as above. Country-level aggregations of the mean age of the population and the proportion of people who believe that environmental protection takes priority over economic growth could be calculated and then plotted against each other.
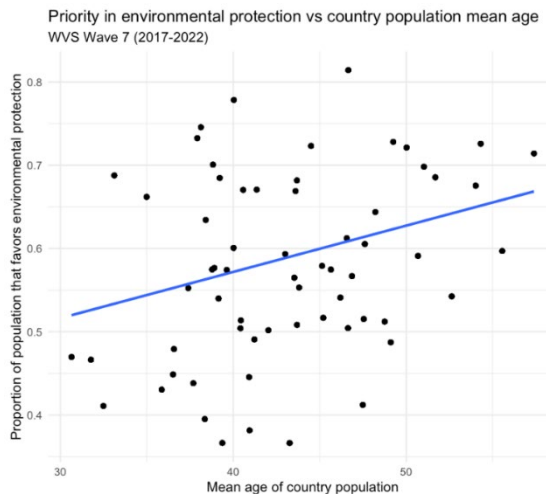
Figure 2. *Proportion of country's population that favors environmental protection over economic growth compared to the mean age of the country's population. A dummy variable to represent the proportion of a population that values environmental protection over the economy was created and a linear regression was fit to the model.*

According to the hypothesis, the mean country age and the proportion of the population that favors the environment should have an inverse relationship, with countries with an older population favoring the environment less than countries with a younger population. It would hence be expected that the slope of the regression model is negative to illustrate this relationship. However, interestingly, the visualization demonstrates a relationship that contradicts the hypothesis with a regression model that has a positive slope. One could simply conclude here that there is a positive relationship between age and environmental concern at the country level but would be too early to have such an assumption due to the possibility of confounding variables. It is important to consider that data does not exist in a bubble and it is often difficult to isolate the impact of a single variable. A confounder is associated with both the independent variable (in this case, age) and the dependent variable (the likelihood to care for environmental protection) and may distort or mask the effect of the independent variable that is currently being studied (Simkus, 2023). In this case, it means that when confounders are not taken into account, the model in

Figure 1.2 might represent the relationship between another variable related to the country's population mean age and environmental concern instead of measuring the direct relationship with age.

One key confounding variable may be the economic status of a country, measured through national incomes (demonstrated using GDP) and economic development (measured through HDI). Higher economic status is seen to have a positive relationship with the likelihood of caring for the environment. One theoretical explanation stems from the hypothesis that as incomes rise, basic needs are met, and people feel a greater sense of existential security, people are more likely to emphasize social and environmental concerns (Liere and Dunlap, 1980). This links to Maslow's hierarchy of needs (Mathes, 1981) and Ingelhert and Welzter's new modernization theory (Inglehart and Welzel, 2005). Simultaneously, economic stability also seems to be related to the independent variable, age. Older populations are often seen to have higher incomes, one reason being that financial resources tend to accumulate as one ages. With more time spent in the workforce, experiences are built, careers gain momentum, and incomes tend to rise (Peterson et al., 2020). Higher national income could also lead to older populations by increasing the life expectancy of the population. GDP per capita explains around 64% of the variation in a country's life expectancy, which could be explained by the idea that richer countries are better able to pay for medical care and technology than developing countries (Jetter, 2016). Simply put, "higher incomes permit countries to buy longevity" (Jetter, 2016) and hence develop an older population. HDI could also be a more comprehensive measure of the country's economic conditions as it takes into account life expectancy, income, and education level together. Consequently, the income level of a country could be a confounding variable that needs to be addressed.

Other important confounders could include the political leaning of the population as well as their average education level. Previous studies have reported that political leaning does have a relationship with support for environmental protection, often with people with left-wing political stances, or more "liberal" opinions, showing greater support (Pew Research, 2017) (Barnett, 2019). A theoretical reason behind this comes from the core values that the two opposing political orientations hold. According to the anti-reflexivity thesis, the reason for climate change skepticism and reluctance to engage in environmental conservation by right-wing individuals is because they focus on upholding the capitalistic system, which is often seen to be threatened by environmental protection policies (McCright et al., 2016). The values also tend to be more individualistic, focusing more on personal gains in the present. In contrast, aligned with their egalitarian values, left-wing individuals are more concerned about the worldwide consequences of climate change and environmental degradation and hence more likely to support environmental protection (Gregersen et al., 2020).

Higher education levels also seem to be linked to greater tendencies to value the environment, especially with "comparative" environmental concerns [2] (Clery and Rhead, 2013). It is likely that higher levels of education allow individuals to gain a better understanding of the anthropogenic causes and global consequences of environmental degradation. With greater awareness of the problem comes an increased likelihood of emphasis on environmental protection (Magali and Anne, 2022).

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[2] According to Clery and Rhead (2013), "comparative environmental concern" refers to a method of measuring environmental concern where individuals are asked to "prioritize a range of different areas of potential concern, including the environment." This aligns with the "Environment vs. Economy" variable this paper is primarily focusing on.

In order to take into account these possible confounding variables and try to isolate the impact of age on environmental attitudes, five different regressions considering the confounders mentioned above were performed.

Table 1. *Regression analysis of the relationship between mean age of country population and likelihood to value the environment with HDI, GINI coefficient, and countries taken into account. Astricts show statistical significance[3]*

	(1)	(2)	(3)	(4)	(5)
(Intercept)	0.350***	0.347***	0.337***	-0.040***	7.442***
	(0.003)	(0.002)	(0.003)	(0.004)	(0.000)
mean_age	0.006***		0.001***	0.005***	-0.366***
	(0.000)		(0.000)	(0.000)	(0.000)
HDI		0.308***	0.273***	0.155***	4.943***
		(0.003)	(0.005)	(0.005)	(0.000)
GINI				0.008***	0.105***
				(0.000)	(0.000)
countryARM					3.548***
					(0.000)
countryAUS					4.757***

The first two regressions illustrate the relationship between the independent variables of the mean age of the country population and HDI with the dependent variable of the likelihood to value the environment respectively. As seen previously in the regression line in Figure 1.2, the regression analysis also presents that the mean age of the country population alone does seem to have a slight positive relationship with the likelihood of favoring the environment, but not to a statistically significant degree. The second regression was included to demonstrate that the proposed confounding variable does indeed affect the dependent variable, and as expected, HDI seems to have a statistically significant positive relationship with environmental values.

The last three regressions then take into account the confounding variables when determining the relationship between mean population age and environmental concern. The third considers HDI alone, and the fourth also includes the GINI coefficient. For both of these regressions, the mean population age seems to have a negligible effect on environmental preference, with the effect of age being 0.000 and 0.004 respectively. Taking into account the larger impact of HDI (0.327) on environmental concerns, this could suggest that the effect of HDI and GINI (which demonstrates the economic status of the country as mentioned before) actually dominates over the effect of age, our original independent variable, rendering the age effect close to zero.

However, in the fifth regression when country-level differences were additionally taken into account, it can be seen that the mean population age now has a negative impact of -0.366 on the likelihood to prefer environmental protection over economic growth. The effect of age now aligns with the hypothesis, showing an

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[3] ^^ + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

indirect relationship with the dependent variable. Perhaps this indicates how country-level differences are accounted for, within each country the effect of age on the likelihood of valuing the environment is negative.

WVS Time Series

Having explored the effect of age at a given period of time (WVS 7), it can also be useful to take advantage of the longitudinal data available from the WVS and observe data over a longer time period to see whether the age effects also appear over time and whether the generational effect can be observed as well. As previously seen in Figure 1.1, it was important to first observe whether the differences in individual environmental values across age groups existed consistently over time and whether there were changes in the relationship over the different survey waves.
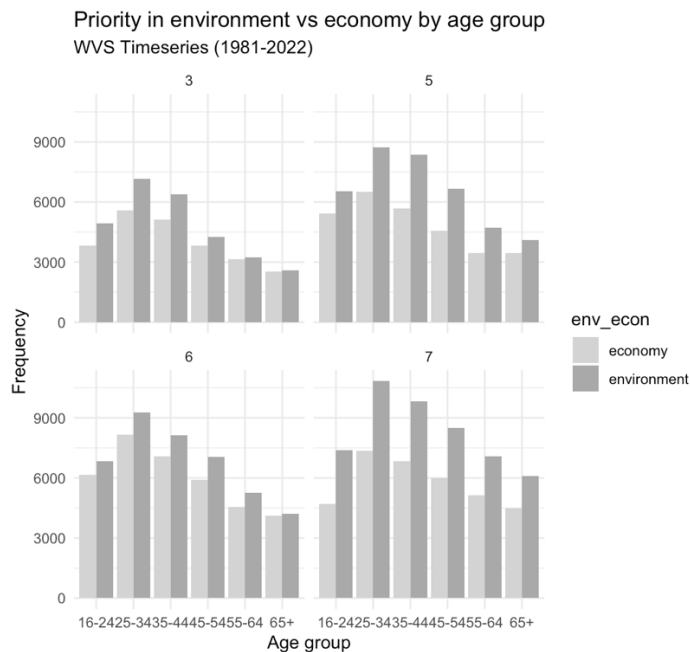
Figure 3. *Priority in given value type by age groups among all individuals surveyed in the WVS, faceted by WVS waves: wave 3 (1995-1998), 5 (2005-2009), 6 (2010-2014), and 7 (2017-2022)*

The overall relationship between age and environmental concern seems to be consistent over time with the proportion of people favoring the environment over the economy decreasing as the age group increases from 25-34 years old to 65+ years old. In wave 3 and wave 6, the proportion of people favoring the economy versus the environment seems to be almost identical at age 65 and above. It is interesting that the 25-34 age group consistently shows the largest proportion of individuals prioritizing environmental action (although less so in wave 6), even compared to the younger 16-24 age group.

Moreover, larger differences between values can be seen in waves 5 and 7 compared to waves 3 and 6. The reason for this difference could be attributed to

significant environmental activism and awareness events that happened during waves 5 and 7. For instance, the Kyoto Protocol, an international treaty operationalized by the United Nations Framework Convention on Climate Change and signed by 192 parties aiming to reduce global greenhouse gas emissions, entered into force on 16 February 2005 (United Nations Climate Change, 2023) while the Bali Climate Summit happened in December 2007 in an attempt to create a new pact that would follow the Kyoto Protocol (Aldred, 2007). Then, as mentioned in the introduction, 2019 was the year of Global Climate Strikes with much heightened awareness, especially amongst the youth, about climate change. Extinction Rebellion, a UK-based environmental organization founded in 2018, also began "non-violent civil disobedience" actions against environmental destruction during a similar time period (BBC, 2022). These international discussions would have brought the issues of climate change and environmental protection to the public during the two waves as well.

In order to further this exploration, individual-level time series data was used to perform four different regression analyses of the impact of age on environmental concerns. Some possible confounding variables mentioned above as well as added variables from the WVS time series, including education level, country, WVS waves, and generation were accounted for in the regressions below.

Table 2. *Regression analysis of the relationship between mean age of country population and likelihood to value the environment with education level, country, WVS waves, and generation taken into account. Astricts show statistical significance.*[4]

	(1)	(2)	(3)	(4)
(Intercept)	0.578***	0.634***	0.542***	0.537***
	(0.003)	(0.003)	(0.017)	(0.022)
age	0.000***	0.000+	-0.001***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
education_levellower		-0.106***	-0.095***	-0.094***
		(0.003)	(0.003)	(0.003)
education_levelmiddle		-0.084***	-0.069***	-0.069***
		(0.002)	(0.002)	(0.002)
wave			0.005***	0.006***
			(0.001)	(0.001)
generationsilent				0.005
				(0.009)
generationboomer				0.016
				(0.011)
generationgenx				0.009
				(0.013)
generationmillenial				-0.007
				(0.015)

The first regression simply looks at the effect of an individual's age on prioritizing the environment across the 4 waves, which is seen to have negligible results. Even when education level is taken into account in the second regression, the effect of age is close to zero. However, these results are understandable because the data used was collected over time and the age and education level of an individual would have shifted over the periods of survey collection. As soon as the WVS waves

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[4] ^^ + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

and countries were considered in the regression analysis, it could be seen that the effect of age, although still minimal, became negative and statistically significant. This means that within each wave, an increase in age is associated with decreased concern about the environment, aligning with the initial hypothesis. In addition, generation was added as another variable in the fourth regression. Generations were separated into five categories: "Greatest Generation," "Silent Generation," "Baby Boomers," "Generation X," and "Millennials." The Greatest Generation included anyone born before 1925. These individuals came of age during the Great Depression and either fought in World War II or worked in industries that contributed to the war. The other four categories were adopted from Gray et al. (2019) and descriptions regarding those characteristics can be found in their paper. The fourth regression still yielded the same results, indicating that even with generational differences, age does seem to have an inverse relationship with environmental concerns.

6. Conclusion

This paper explored possible age and birth cohort effects on the likelihood of one to value environmental protection through a cross-cultural and longitudinal analysis of the WVS. Although there were multiple confounding variables to consider in the process, it seems as though the hypothesis of a positive relationship between age and environmental concerns holds true at the individual level and across time.

It is important to note that, despite positive attitudes towards environmental conservation, it is difficult to conclude yet that high levels of environmental concern directly translate to willingness and ability to act in favor of environmental protection. It would be worth observing other WVS variables, such as membership or degree of participation in an environmental organization, involvement in protest or climate activism, or concerns about pollution and environmental degradation to further develop the line of inquiry and explore whether pro-environmental values also result in greater environmental concern.

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The Code in the Hat: Hamming Codes Applied to Ebert's Hat Puzzle

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Abstract

This paper follows the work of Guo et al. in their article "The Hat Problem and Some Variations." We explore the application of Hamming codes to Ebert's Hat Problem, incorporating graph theory into the discussion. We further develop the classic problem by examining the general case of n cats and q hat colors. While there is not an optimal solution to greater than two hat colors using Hamming codes, we show that this technique still increases the probability of winning over standard probabilistic strategies.

1. Introduction

Hat problems, a type of induction puzzle, have been used for years to study and further the fields of probability, game theory, computer science, and beyond [1][2][3]. Typically, these problems involve a player using probability or logic to guess the color of their own hat based on the colors of the other players' hats. The optimal technique to solving the problem differs with each problem's specific parameters. In one specific instance, Todd Ebert offered the following thought puzzle, initially posed as a prisoner puzzle in his 1998 PhD thesis in Mathematics from the University of California, Santa Barbara [4]. Hereafter, this is termed Ebert's Hat Puzzle and restated to match the scope of this paper.

> There are three cats: Buttons, Mittens, and Whiskers. They are perfectly logical cats, but often find themselves in trouble. The three happened upon a room. When they walked in, the door closed and locked behind them. They saw a board on the wall outlining the rules of a game.

> Guess the color of your hat to escape! The rules are as follows:
> - No player can see their own hat color, but they can see every other player's hats.
> - No communication is allowed except for a planning meeting before the game starts.
> - A random color hat (red-banded or black-banded) will then be placed on each player's head.
> - Each player can either guess their hat color or pass.
> - All players will guess simultaneously.
> - The players will walk free if all players who guess, guess correctly.
> - The players will be confined indefinitely if at least one player guesses incorrectly or if all players pass.

What should Buttons, Mittens, and Whiskers do to maximize their chance of escaping?

Figure 1 shows Ebert's Hat Puzzle as experienced by Buttons, Mittens, and Whiskers. Each of the cats can see each other's hats but cannot see their own. In this instance, both Buttons and Whiskers are wearing red-banded hats while Mittens is wearing a black-banded hat.

Figure 1. *Ebert's Hat Puzzle, as experienced by Buttons (left), Mittens (center), and Whiskers (right).*

Ebert's optimal solution to the puzzle he posed was to incorporate Hamming codes, a type of error correction. This novel approach gained immediate attention around technical circles and was even covered in the New York Times [5]. While the relationship between Ebert's Hat Puzzle, Hamming codes, and graph theory is not immediately obvious, the goal of this paper is to use both Hamming codes and graph theory to come up with a strategy that will allow any future cats who find themselves in this unfortunate situation to maximize their chances of escaping.

2. Technical Preliminaries

2.1. Hamming Codes

Error detection and correction is important in data communication. In 1950, Richard W. Hamming worked at Bell Laboratories. The punched card readers he used, a computer input system from that time, often introduced errors. While the system did have a form of error detection, it would freeze, not knowing what to do next. Sometimes the freeze would happen on a weekend, losing valuable computing time. This especially bothered Hamming because no one would be around to fix the error until Monday. Hamming figured that if the computer could detect errors, there should be a way for the computer to correct those errors. This led to his groundbreaking paper

in the field of error detection and correction codes, now known as *Hamming codes* [6][7].

Error correction would be easy if there was access to infinite data space because one could just copy the information three or more times. If any part of the data differs from the other copies, there is good chance it is incorrect, and the other copies can be used to correct the data. The extra copies of data are called *redundant bits*. Hamming's novel approach was to make self-correcting codes that had as little redundancy as possible. Hamming codes use parity of the bits to identify where an error has occurred. With multiple parity bits that cleverly cover the data bits, Hamming's technique can also correct the error. Hamming's technique is generally applicable but works best in applications with infrequent errors.

The field of error detection and correction has advanced significantly since Hamming's initial discovery. In fact, Hamming codes are no longer widely used in practice for data communication. However, there are still practical uses for Hamming's technique, such as in error correcting code (ECC) random access memory (RAM), where there is a low occurrence of bit errors [8].

As used in this paper, a *digit* is a numerical value of any base. A *message* is a collection of digits that are being transmitted from the *sender* to the *receiver*. Additional redundant digits are added to the message, resulting in a *word*. The redundant digits are used to determine the parity of the overall message and to determine if any digits were corrupted during transmission. The resulting word is a collection of n digits with q states each. For example, "101" is an example of a binary ($q = 2$) word with $n = 3$ bits, and "2102" is an example of a ternary ($q = 3$) word with $n = 4$ trits. A *codeword* is defined as a word where the values of the redundant parity digits agree with the message and indicate the word has not been corrupted. A set of codewords is called a *code* which is denoted as $\mathbb{C}$. A *non-codeword* is a word that is not a codeword.

Until Section 4 of this paper, we will assume all digits are bits ($q = 2$).

Let u and v be codewords in code $\mathbb{C}$. The *Hamming distance* between u and v, denoted as $d(u,v)$, is calculated by counting how many bits differ between u and v. As stated previously, n is the length of each word, including each codeword.

$$d_i(u,v) \;=\; |u_i - v_i| \tag{1}$$

$$d(u,v) = \sum_{i=1}^{n} d_i(u,v) = \sum_{i=1}^{n} |u_i - v_i| \tag{2}$$

For example,

$$d(0101, 1111) = 2$$
$$d(0011, 1100) = 4.$$

The properties for Hamming distances are

$$d(u,v) \geq 0 \tag{HP1}$$

$$d(u,v) = 0 \Leftrightarrow u = v \tag{HP2}$$

$$d(u,v) = d(v,u) \tag{HP3}$$

$$d(u,v) \leq d(u,w) + d(w,v) \tag{HP4}$$

where w is also a codeword.

Theorem 1. *Hamming distance property HP1: $d(u,v) \geq 0$.*

Proof. Let both u and v be codewords in code $\mathbb{C}$. Then, by equation 1, $d_i(u,v) = |u_i - v_i|$. An absolute value of any real number is always greater than or equal to zero. So, $d_i(u,v) \geq 0$ for each index i.

The addition of positive numbers can only result in another positive number, and the addition of zero will not change the value. Therefore, when summing over all indices which each consist of only zero or positive numbers, the result will also be zero or positive.

Therefore, $d(u,v) \geq 0$.

∎

Theorem 2. *Hamming distance property HP2: $d(u,v) = 0 \iff u = v$.*

Proof. Let both u and v be codewords in code $\mathbb{C}$.

First, let us prove $d(u,v) = 0 \implies u = v$ by counterexample.

By equation HP1 we know $d(u,v) \geq 0$. Substituting equation 2,

$$d(u,v) = \sum_{i=1}^{n} d_i(u,v) = \sum_{i=1}^{n} |u_i - v_i| \geq 0.$$

Let us first assume that $d(u,v) = 0$. Let us also assume that $u \neq v$, which means there must be at least one index j where $u_j \neq v_j$. Since subtraction only results in zero when the two numbers are equal, $d_j(u,v) = |u_j - v_j| > 0$ for each index j. For all other indices i where $u_i = v_i$, this implies $d_i(u,v) = |u_i - v_i| = 0$. Summing over all indices, $d(u,v) > 0$, which is a contradiction to the first assumption. Therefore, if $d(u,v) = 0$ there cannot exist an index j where $u_j \neq v_j$. Stated alternatively, $u_i = v_i$ for all indices i and $u = v$.

Therefore,

$$d(u,v) = 0 \implies u = v. \tag{3}$$

Next, let us prove the converse $u = v \implies d(u,v) = 0$.

Let $u = v$. We then know $d_i(u,v) = 0$ for each index i since subtraction of equivalent values is zero. From this, when we sum over all indices i, the result is zero.

Therefore,

$$u = v \implies d(u,v) = 0. \tag{4}$$

Combining equations 3 and 4, $d(u,v) = 0 \iff u = v$.

∎

Theorem 3. *Absolute value property: $|a||b| = |ab|$.*
(Used in Theorem 4 to prove Hamming distance property HP3)

Proof. Let both a and b be real numbers. Given the multiplication of $|a||b|$, we will square it, yielding $(|a||b|)^2$. Via laws of exponents, we will apply the square to both individually, resulting in $|a|^2|b|^2$. Because squaring a real number always results in a positive number, $|a|^2|b|^2 = a^2 b^2$. By refactoring the expression, we get $(ab)^2$ which is equal to $|ab|^2$ for the same reason previously shown. Therefore $(|a||b|)^2 = |ab|^2$. Taking the square root of both sides results in

$$|a||b| = |ab|. \tag{5}$$

∎

Theorem 4. *Hamming distance property HP3: $d(u,v) = d(v,u)$.*

Proof. Let both u and v be codewords in code $\mathbb{C}$. From equation 1, $d_i(u,v) = |u_i - v_i|$, which is equal to $|-1||u_i - v_i|$. From equation 5, $|a||b| = |ab|$, where a and b are real numbers, so $|-1||u_i - v_i| = |-1(u_i - v_i)|$. Distributing the -1 and rearranging the terms, we result in $|v_i - u_i|$. Since $|u_i - v_i| = |v_i - u_i|$, summing over all i on both

sides gives

$$\sum_{i=1}^{n} d_i(u,v) = \sum_{i=1}^{n} d_i(v,u).$$

From equation 2 this translates to

$$d(u,v) = d(v,u).$$

∎

Theorem 5. *Absolute Value Property* $|a+b| \leq |a| + |b|$.
(Used in Theorem 6 to prove Hamming distance property HP4)

Proof. Let both a and b be real numbers. Given the addition of $|a| + |b|$, we will square it, yielding $(|a| + |b|)^2$. Expanding the expression, we get $|a|^2 + 2|a||b| + |b|^2$. Because squaring a real number always results in a positive number, $|a|^2 + 2|a||b| + |b|^2 = a^2 + 2|a||b| + b^2$. From equation 5, this simplifies to $a^2 + 2|ab| + b^2$. Since $|ab|$ is always positive while ab can be negative or positive, $|ab| \geq ab$. Therefore, $a^2 + 2|ab| + b^2 \geq a^2 + 2ab + b^2$. Factoring both sides, we get, $(|a| + |b|)^2 \geq (a+b)^2$. Again, since squaring a real number always results in a positive number, $(a+b)^2 = |a+b|^2$. Combining the previous equations, $(|a| + |b|)^2 \geq |a+b|^2$. Lastly, taking the square root of both sides and rearranging the inequality results in

$$|a+b| \leq |a| + |b|. \tag{6}$$

∎

Theorem 6. *Hamming distance property HP4:* $d(u,v) \leq d(u,w) + d(w,v)$.

Proof. Let u, v, and w be codewords in code $\mathbb{C}$. From equation 1, we know $d_i(u,v) = |u_i - v_i|$. Because $w_i - w_i$ is zero, adding it within the absolute value does not change the total value of $d_i(u,v)$. Therefore, $|u_i - v_i| = |u_i - v_i + w_i - w_i|$. Rearranging the values results in $|(u_i - w_i) + (w_i - v_i)|$. From equation 6, $|a+b| \leq |a| + |b|$, where a and b are real numbers, so $|(u_i - w_i) + (w_i - v_i)| \leq |u_i - w_i| + |w_i - v_i| = d_i(u,w) + d_i(w,v)$. Summing over all i on both sides of the inequality gives

$$\sum_{i=1}^{n} d_i(u,v) \leq \sum_{i=1}^{n}[d_i(u,w) + d_i(w,v)].$$

Distributing the summation to each individual term results in

$$\sum_{i=1}^{n} d_i(u,v) \leq \sum_{i=1}^{n} d_i(u,w) + \sum_{i=1}^{n} d_i(w,v).$$

From equation 2, this translates to

$$d(u,v) \leq d(u,w) + d(w,v).$$

∎

2.2. Graph Theory

The concepts of Hamming codes and distances work well with graph theory. For the purposes of this paper, let each vertex represent a word and each edge represent one digit change between adjacent words.

Let the minimum Hamming distance between codewords within code $\mathbb{C} = \delta$. In other sources, they may use d. However, for the purposes of not confusing this with the Hamming distance function $d(u,v)$, we will use δ in this paper. For example, let us consider a set of all possible 3-bit binary words with codewords

represented by the code $\mathbb{C} = \{000,011,100\}$. This is graphically represented in figure 2. From equation 2, it can be easily seen that within code $\mathbb{C}$, $d(000,011) = 2$, $d(011,100) = 3$, and $d(000,100) = 1$. Therefore, $\delta = min(1,2,3) = 1$ for code $\mathbb{C}$. To restate a critical detail, δ is the minimum distance between all codewords only. It is unaffected by the distance between codewords and any other words. In figure 2, we can also see that $d(u,v)$ can be determined graphically by tracing the minimum number of vertices to travel between codewords. Once an edge is traversed, we will not use it again because if a bit changes twice, it will return to its original position, meaning the move was redundant. This example, and the general concepts of graph theory, can be easily generalized to the situation of an arbitrary set of n-bit binary words, which will have 2^n total words and a set of codewords $\mathbb{C}$ where $|\mathbb{C}| \leq 2^n$.
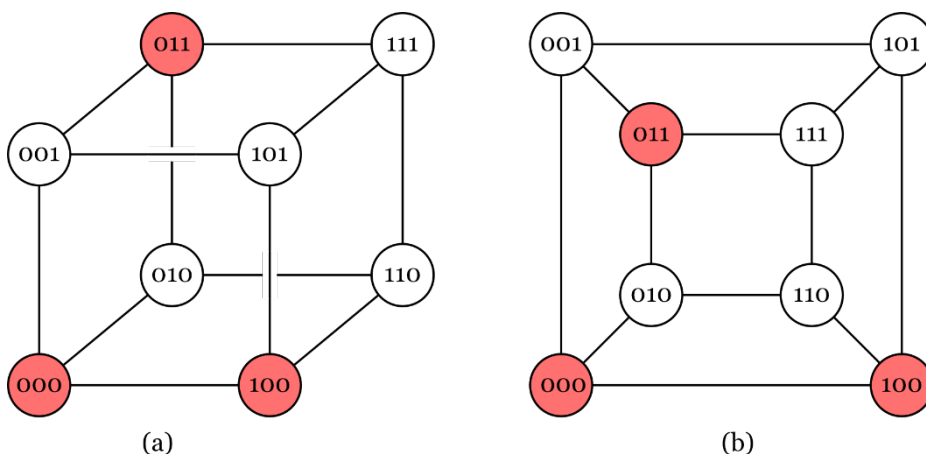
Figure 2. *Graph theory depictions of all possible 3-bit binary words in (a) 3-dimensional and (b) cube graph representations. In both cases, vertices colored red indicated the codewords within the code $\mathbb{C}$.*

In relation to Hamming codes, the concept of minimum Hamming distance δ is also important in determining the number of errors (corrupted words) that can be detected and corrected. Specifically, for a given set of words and codewords, a maximum of $\delta - 1$ errors can be detected, of which a maximum of $\left\lfloor \frac{\delta-1}{2} \right\rfloor$ can be corrected.

Theorem 7. *The maximum number of detectable errors is $\delta - 1$.*

Proof. Let u, v, w, and x be codewords in code $\mathbb{C}$. Further, let u and v be the closest codewords in code $\mathbb{C}$.

Since δ is the minimum Hamming distance within code $\mathbb{C}$ where u and v are the closest codewords in code $\mathbb{C}$, by definition there are δ edges from u to v and vice versa. From graph theory, we know the number of vertices is one more than the number of edges. Therefore, on the path from u to v, there are $\delta + 1$ vertices. Since the receiver expects a codeword, they can detect an error as long as the received message is not a codeword. Because a received message that contains an error cannot be the endpoints u nor v, there are $\delta - 1$ non-codeword vertices on the path u to v. This means there are $\delta - 1$ detectable errors before reaching another codeword.

Now, let us consider the path from w to x. Let $d(w,x) = \Delta$. With the same

logic as shown previously, there are $\Delta - 1$ detectable errors between w and x. However, because δ is the minimum distance in code $\mathbb{C}$ and $\delta \leq \Delta$, we can only state that the maximum number of *guaranteed* detectable errors is $\delta - 1$ regardless of the value of Δ.

∎

For example, in figure 3(a), $\delta = 4$ and there are $\delta - 1 = 3$ corrupted words, a, b, and c between u and v that can be detected. Similarly, in figure 3(b), $\delta = 3$ and there are $\delta - 1 = 2$ corrupted words, a and b between u and v that can be detected.

(a)   (b)
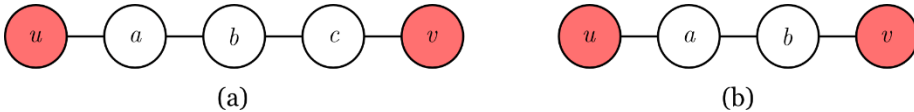
Figure 3. *Example of corrupted words a, b, and c between codewords u and v, which in turn are separated by the minimum Hamming distance δ. Shown are cases where (a) δ is even, and (b) δ is odd.*

The ability to not only detect errors, but to also correct those errors, is integral to Hamming codes and part of the reason Hamming originally developed the concept. While a maximum of $\delta - 1$ errors can be detected, not all those errors can be uniquely corrected. For example, a word that is equidistant from its two closest codewords cannot be uniquely corrected to either codeword. This bounds the upper limit on how many errors in a corrupted word can be corrected to $\left\lfloor \frac{\delta - 1}{2} \right\rfloor$.

Theorem 8. *The maximum number of correctable errors is* $\left\lfloor \frac{\delta - 1}{2} \right\rfloor$.

Proof. Let u and v be the closest codewords in code $\mathbb{C}$ such that the Hamming distance between them is δ. A correction strategy will always choose to correct an error to the nearest codeword. To be closer to one endpoint than another, the vertex must be less than half the distance away from one of the endpoints.

First consider the case where δ is odd. There are an odd number of edges and $\delta - 1$ (an even number of) vertices between u and v. In this case, it is not possible to be at a word that is equidistant from u and v, and there are no ambiguous cases where the code will not correct to the appropriate codeword. Because there are guaranteed at least $\delta - 1$ vertices between any two codewords in code $\mathbb{C}$, the number of guaranteed correctable errors is $\frac{\delta - 1}{2}$.

Now consider the case where δ is even. There are an even number of edges and $\delta - 1$ (an odd number of) vertices between u and v. In this case, there is one vertex that is equidistant to both endpoints, and the receiver will not be able to uniquely determine whether one endpoint is correct over the other. Disallowing the ambiguous case, there are guaranteed at least $\delta - 2$ vertices between any two codewords in code $\mathbb{C}$ that will correct to the appropriate codeword. Therefore, the number of guaranteed correctable errors is $\frac{\delta - 2}{2}$ or $\frac{\delta}{2} - 1$.

Let β represent the number of guaranteed correctable errors. Therefore,

$$\beta = \begin{cases} \frac{\delta - 1}{2} & \text{if } \delta \text{ is odd} \\ \frac{\delta}{2} - 1 & \text{if } \delta \text{ is even.} \end{cases}$$

Because both β and δ are natural numbers, the above can be reduced to

$$\beta = \left\lfloor \frac{\delta - 1}{2} \right\rfloor.$$

∎

For example, in figure 3(a) where $\delta = 4$, there are $\delta - 1 = 3$ corrupted words, a, b, and c that can be detected, but not all of them can be corrected accurately. Assuming the correct codeword is u, only a can be accurately corrected since it is nearest to u. By contrast, c would be incorrectly corrected to v, and b cannot be uniquely corrected to either u or v. Thus, only one out of the three errors can be corrected $= \left\lfloor \frac{\delta - 1}{2} \right\rfloor = \left\lfloor \frac{3}{2} \right\rfloor = 1$.

In figure 3(b) where $\delta = 3$, there are $\delta - 1 = 2$ corrupted words, a and b that can be detected, but only one can be corrected accurately. Assuming the correct codeword is u, a can be accurately corrected since it is nearest to u. By contrast, b would be incorrectly corrected to v. Thus, only one out of the two errors can be corrected $= \left\lfloor \frac{\delta - 1}{2} \right\rfloor = \left\lfloor \frac{2}{2} \right\rfloor = 1$.

3. Ebert's Hat Puzzle with Three Cats ($n = 3$) and Two Hat Colors ($q = 2$)

In this first instance of Ebert's Hat Puzzle, we consider the case where there are two different hat colors ($q = 2$): red-banded hats (R) and black-banded hats (B), as illustrated in figure 1. The number of cats participating in the puzzle, n, is arbitrary as long as $n \geq 1$, or stated another way, $n \in \mathbb{N}$.

Goal: Come up with a strategy that will allow the n cats to escape with high probability, meaning the probability of winning, $p_{\text{win}} \to 1$ as $n \to \infty$.

3.1. Strategy 1: *Each cat randomly guesses the color of their hat*

This strategy is trivial. Each of the n cats has a probability of $\frac{1}{2}$ to guess the correct color of their own hat. Using basic statistics, the overall probability of winning is $p_{\text{win}} = \left(\frac{1}{2} \right)^n$.

For Ebert's Hat Puzzle as presented in this paper with 3 cats and 2 hat colors, the probability that Buttons, Mittens, and Whiskers will escape using Strategy 1 is $p_{\text{win}} = \left(\frac{1}{2} \right)^3 = \frac{1}{8} = 0.125$.

3.2. Strategy 2: *Each cat randomly passes or guesses the color of their hat*

In this strategy, the number of choices has increased by one (the option to pass), and the denominator is now 3^n. Using the configuration in figure 1 as an example, when none of the cats pass, there is only $\binom{3}{3} = 1$ configuration for a win (RBR). When one cat passes, there are $\binom{3}{2}$ configurations that will win (PBR, RPR, and RBP), where P means that cat decided to pass. Furthermore, when two cats pass, there are $\binom{3}{1}$ winning configurations (PPR, PBP, and RPP). Extrapolating to i passes for n cats, there are $\binom{n}{n-i}$ winning configurations. When every cat passes, as stated in the puzzle

rules, they all lose. Therefore, summing the total number of winning configurations (the numerator) results in $\sum_{i=1}^{n}\binom{n}{n-i}$. Dividing the total number of winning configurations by the total number of configurations gives

$$p_{\text{win}} = \frac{1}{3^n}\sum_{i=1}^{n}\binom{n}{n-i}. \tag{7}$$

Theorem 9. *Pascal's Identity: for any natural numbers n and k where $n \geq k$,*
$\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$.
(Used in Theorem 10)

Proof. Let n and k be natural numbers where $n \geq k$.

Given $\binom{n-1}{k-1} + \binom{n-1}{k}$, we can expand the expression to

$$\binom{n-1}{k-1} + \binom{n-1}{k} = \frac{(n-1)!}{(k-1)![(n-1)-(k-1)]!} + \frac{(n-1)!}{(k)![(n-1)-(k)]!}$$
$$= \frac{(n-1)!}{(k-1)!(n-k)!} + \frac{(n-1)!}{(k)!(n-k-1)!}.$$

Factoring $(n-1)!$ out of both terms yields

$$(n-1)!\left[\frac{1}{(k-1)!(n-k)!} + \frac{1}{(k)!(n-k-1)!}\right].$$

To add the two fractions, we must find the least common multiple of the two denominators which is $(k)!\,(n-k)!$. Multiplying the first term by $\frac{k}{k}$ and the second by $\frac{n-k}{n-k}$ gives

$$(n-1)!\left[\frac{k}{(k)!(n-k)!} + \frac{n-k}{(k)!(n-k)!}\right].$$

Adding the two fractions gives a numerator within the parenthesis of n which can be combined with $(n-1)!$ into $n!$. The above equation can then be simplified to

$$\frac{(n)!}{(k)!(n-k)!}$$

which is the formula of $\binom{n}{k}$.

Therefore,

$$\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}. \tag{8}$$

∎

Theorem 10. *For any natural number n, $\sum_{i=0}^{n}\binom{n}{i} = 2^n$.*

Proof. Let n be a natural number. We will prove $\sum_{i=0}^{n}\binom{n}{i} = 2^n$ using induction.

When $n = 1$, $\sum_{i=0}^{1}\binom{1}{i} = \binom{1}{0} + \binom{1}{1}$ which is $2 = 2^1$. Therefore, for the $n = 1$ case, the proposition holds true.

Let us assume the following equation hold true:

$$\sum_{i=0}^{n}\binom{n}{i} = 2^n$$

and then see if the equation holds true for the case $n + 1$.

$\sum_{i=0}^{n+1}\binom{n+1}{i}$ can be expressed as $\binom{n+1}{0} + \binom{n+1}{1} + \cdots + \binom{n+1}{n} + \binom{n+1}{n+1}$. Using Pascal's identity from equation 8, we can rewrite each term, except the first and last, resulting in

$$\binom{n+1}{0} + \left[\binom{n}{0} + \binom{n}{1}\right] + \left[\binom{n}{1} + \binom{n}{2}\right] + \cdots + \left[\binom{n}{n-1} + \binom{n}{n}\right] + \binom{n+1}{n+1}.$$

Since $\binom{n+1}{0}$ is the same as $\binom{n}{0}$ and $\binom{n+1}{n+1}$ is the same as $\binom{n}{n}$, we can rewrite those terms and regroup as

$$\left[\binom{n}{0} + \binom{n}{0}\right] + \left[\binom{n}{1} + \binom{n}{1}\right] + \cdots + \left[\binom{n}{n-1} + \binom{n}{n-1}\right] + \left[\binom{n}{n} + \binom{n}{n}\right].$$

We can now see there are two copies of each term $\binom{n}{0}$ through $\binom{n}{n}$. Therefore, the above expression is equal to $2\sum_{i=0}^{n}\binom{n}{i}$. Because of our initial assumption, this is equivalent to $2 \cdot 2^n = 2^{n+1} = \sum_{i=0}^{n+1}\binom{n+1}{i}$, which proves case $n + 1$ holds true.

Therefore, by induction, for all natural numbers n,

$$\sum_{i=0}^{n}\binom{n}{i} = 2^n. \tag{9}$$

∎

We can use equation 9 to simplify equation 7. The summation portion is $\sum_{i=1}^{n}\binom{n}{n-i}$. From combinatorics, we know that this is the same as $\sum_{i=1}^{n}\binom{n}{i}$. This sum is also equivalent to $\sum_{i=0}^{n}\binom{n}{i} - 1$ because $\binom{n}{0} = 1$. Therefore, equation 7 can be simplified to:

$$p_{\text{win}} = \frac{2^n - 1}{3^n}. \tag{7'}$$

For Ebert's Hat Puzzle as presented in this paper with 3 cats and 2 hat colors, the probability that Buttons, Mittens, and Whiskers will escape using Strategy 2 is $p_{\text{win}} = \frac{2^3 - 1}{3^3} = \frac{7}{27} = 0.259$, a significant increase from Strategy 1.

3.3. Strategy 3: *One cat randomly guesses the color of their hat while the other cats pass*

In this strategy, Buttons, Mittens, and Whiskers decide beforehand to a set of rules:

- Buttons will randomly guess the color of their hat.
- Mittens and Whiskers will each pass.

The overall probability of winning with this strategy is $p_{\text{win}} = \frac{1}{2}$ since only one cat is guessing while the other cats pass.

For Ebert's Hat Puzzle, as presented in this paper, with 3 cats and 2 hat colors, the probability that Buttons, Mittens, and Whiskers will escape using Strategy 3 is $p_{\text{win}} = \frac{1}{2} = 0.5$, which again shows a significant increase from both Strategies 1 and 2.

3.4. Strategy 4: *Each cat guesses the color of their hat, or passes, depending on the color of the other cats' hats*

As with Strategy 3, in this strategy Buttons, Mittens, and Whiskers must agree beforehand on a set of rules to apply. While many such sets of rules could be devised, it is unclear how to select a set of rules that would maximize p_{win}.

When n is 1 or 2, the best the cats could do is $p_{\text{win}} = \frac{1}{2}$ because there is no additional, usable information in those situations. However, when $n = 3$, we can start implementing specific rule sets that could increase the chances of escaping. In fact, Guo et al. indicated that for low values of n and q, it is feasible to numerically try all possibilities and find the best rule set [1]. However, for the specific case of $n = 3$, Ebert already provided a solution in the form of Hamming codes [4]. Paraphrased, the rules are as follows:

- Any cat that sees two hats of the same color will choose the opposite color.
- Any cat that sees two hats of different colors will pass.

In table 1, we can see that when applying these rules to all hat permutations, the cats each correctly guess six times and incorrectly six times, but collectively win $\frac{6}{8}$ times overall, which is a significant improvement from prior strategies.

Table 1. *All possible two-color hat combinations (q = 2) for the case n = 3, along with guesses and overall outcomes from applying Ebert's Hamming code strategy. B indicates a black-banded hat, R indicates a red-banded hat, and P indicates a pass. Each correct guess is marked with a check (✓), and each incorrect guess is marked with a cross (×).*

Buttons' Hat	Mittens' Hat	Whiskers' Hat	Buttons' Guess	Mittens' Guess	Whiskers' Guess	Outcome
B	B	B	R (×)	R (×)	R (×)	Loss
B	B	R	P ( )	P ( )	R (✓)	Win
B	R	B	P ( )	R (✓)	P ( )	Win
B	R	R	B (✓)	P ( )	P ( )	Win
R	B	B	R (✓)	P ( )	P ( )	Win
R	B	R	P ( )	B (✓)	P ( )	Win
R	R	B	P ( )	P ( )	B (✓)	Win
R	R	R	B (×)	B (×)	B (×)	Loss

One important feature of the results shown in table 1 is that there is an equal number of correct and incorrect guesses. This makes sense when viewed through the lens of cat$_i$. Regardless of what the other cats' hat colors are, cat$_i$ will have a black-banded hat 50% of the time and a red-banded hat 50% of the time. Due to this, whenever cat$_i$ guesses, they will be correct 50% of the time.

Another important point to note is that in this winning set of rules, we "pack" all the bad guesses into a minimum number of configurations. When the cats are in a losing configuration, every cat guesses incorrectly. However, we distribute the winning guesses across the other configurations. In those cases, only one cat guesses correctly and the other cats pass. Therefore, each cat still maintains the 50% chance of guessing correctly overall. However, by spreading out the correct guesses and compounding the incorrect guesses, we can increase the overall chances of a win. Stated another way, this strategy does not improve each cat's probability of correctly choosing the color of their hat, which is still 50%. Rather, this strategy helps them choose when to pass, which increases the overall collective chance of winning.

In the balance of this section, we will show how these rules directly relate to Hamming codes. More specifically, we will show how each losing configuration corresponds to a codeword. Unlike the traditional use of Hamming codes where we try to correct errors and move from a corrupted word to a codeword, in this case we are doing the opposite and are actively trying to avoid the codewords.

Theorem 11. *The Hamming code strategy for n cats and q = 2 hat colors has* $p_{\text{win}} = \frac{n}{n+1}$.

Proof. Let u be a codeword in code $\mathbb{C}$, and let $\mathbb{W}$ be a set of nearby non-codewords with elements $\{w_1, \dots, w_n\}$. Also, let us assume we have a *perfect* Hamming code [7] where

each non-codeword is directly adjacent to a codeword, or $d(u, w_i) = 1$, and the codewords are the same minimum distance $\delta = 3$ apart so that each non-codeword is uniquely related to a single codeword. From these assumptions, it is easy to see that the neighborhood of each codeword is the same: n non-codewords, each connected to a center vertex codeword as seen in figure 4.
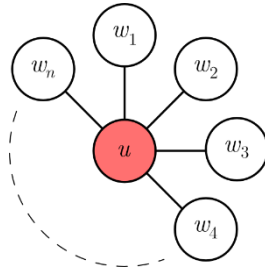
Figure 4. *Graph showing the n connections from codeword u to adjacent non-codewords w_1 through w_n in $\mathbb{W}$.*

In this strategy, we assign each non-codeword as a winning position. If there are x codewords within the entire set of words, then there are xn winning non-codeword configurations and $x(n + 1)$ total configurations. Therefore, the probability of winning using this Hamming code strategy is $p_{\text{win}} = \frac{xn}{x(n+1)}$ or

$$p_{\text{win}} = \frac{n}{n+1}. \tag{10}$$

Of note, this relationship only holds for *perfect* Hamming codes with special cases of $n = n^*$, such as $n = 3$, which will be proven later in this section.
∎

Finally, we need to understand how to translate this Hamming code strategy into something that Buttons, Mittens and Whiskers can understand. If they understood the concept of codewords, they could establish the following:

- For this specific case, depicted in figure 5, the set of codewords $\mathbb{C} = \{BBB, RRR\}$.
- Any cat who sees the possibility of an adjacent codeword will choose the color that will make sure a codeword is not formed. In this case, if a cat sees BB, they will choose R. Similarly, if a cat sees RR, they will choose B.
- Any cat who cannot see the possibility of an adjacent codeword will pass. In this case, if a cat sees BR, they cannot determine which codeword is adjacent, and there is not enough information to make an informed guess, so they pass.

By inspection, these are the same rules that were established at the beginning of this strategy but stated in a different way. Of note, the only cases in which these rules fail are when the starting state is on a codeword. For example, if the starting state is BBB, each cat will see BB and choose R, resulting in an overall guess of RRR, which is a loss. The same logic applies if the starting state is RRR.

Also of note, the Hamming code strategy does not work for every value of n. This restriction can be easily explained in that for this strategy to work, there needs to be a *perfect* Hamming code with n digits, which is only possible for certain values of $n = n^*$.
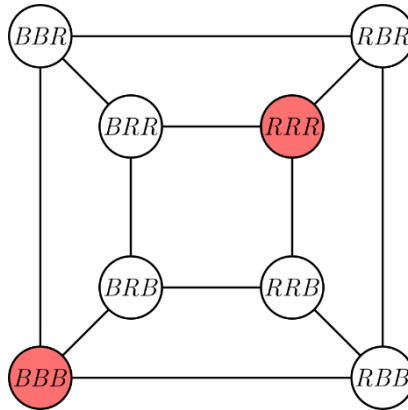
Figure 5. *Cube graph representation of all possible configurations for the two-color Ebert's Hat Puzzle experienced by Buttons, Mittens, and Whiskers. Vertices colored red indicate the codewords, BBB and RRR, which are losing configurations. All other vertices are non-codewords and are winning configurations.*

Theorem 12. *For two hat colors, perfect Hamming codes only exist for special values of n^* when $n^* = 2^r - 1$ where $r \in \mathbb{N}$.*

Proof. For a Strategy 4 Hamming code solution to work, it must be a perfect Hamming code where each possible configuration must be a codeword (losing configuration) or a non-codeword (winning configuration). Furthermore, each winning configuration must be one bit change away from one and only one codeword.

Given n cats, there are 2^n possible hat configurations. Within those configurations, let us assume there are 2^x codewords where $x \leq n$. Because each codeword is connected to n other positions, there must be $n2^x$ non-codewords. Adding all the codewords and non-codewords together, we get a total of $2^x + n2^x$ total words. Because this expression must equal 2^n, we can state $2^n = 2^x + n2^x$. We start by factoring the right-hand side, yielding $2^n = (n + 1)2^x$. Dividing both sides by 2^x, we get $\frac{2^n}{2^x} = n + 1$. Rearranging the exponents, we can reach $2^{n-x} = n + 1$. Because $n + 1$ is a natural number, 2^{n-x} must also be a natural number since for an exponential expression to be discrete where the base is already a natural number, the exponent must also be a natural number. Therefore, $n - x$ is a natural number. Let $n - x = r$. From the above equation, we can see that $2^r = n + 1$ and this relationship only holds for special cases of n^* when

$$n^* = 2^r - 1 \qquad (11)$$

where $r \in \mathbb{N}$.

∎

Summarizing the results from this strategy,

$$p_{win} = \begin{cases} \frac{1}{2} & \text{if } n < 3 \\ \frac{n}{n+1} & \text{if } n \geq 3 \text{ and } n = n^* = 2^r - 1 \text{ where } r \in \mathbb{N}. \end{cases}$$

For Ebert's Hat Puzzle as presented in this paper with 3 cats and 2 hat colors, the probability that Buttons, Mittens, and Whiskers will escape using Strategy 4 is

$p_{\text{win}} = \frac{6}{8} = 0.75$, which is the highest probability of escape for all strategies so far.

Note that this strategy meets our stated goal of allowing the cats to escape with high probability since $\lim\limits_{n\to\infty} p_{\text{win}} = \lim\limits_{n\to\infty} \frac{n}{n+1} = 1$.

3.5. The optimal strategy for two hat colors

An *optimal* strategy or solution is one that results in the highest possible p_{win}. While there may be multiple optimal strategies for a given problem, there cannot be any strategies with a higher p_{win}. For Ebert's Hat Puzzle, it should be evident from the discussion so far that for a strategy to be optimal, there are three things that must be true. First, when the cats win, only one of them guesses and the others pass. Second, incorrect guesses are packed into as few configurations as possible. Third, the total number of correct guesses is equal to the total number of incorrect guesses. An optimal strategy has $p_{\text{win}} = \frac{1}{2^n}\left\lfloor\frac{n2^n}{n+1}\right\rfloor$.

Theorem 13. *Property of the floor function:* $\lfloor a\rfloor = b \iff a - 1 < b \leq a$. *(Used in Theorem 14)*

Proof. Let a be a real number and b be an integer.

First, let us prove if $\lfloor a\rfloor = b$, then $a - 1 < b \leq a$.

Let $\lfloor a\rfloor = b$. By definition of the floor function, $\lfloor a\rfloor$ is the greatest integer less than or equal to a. When a is an integral value, $b = a$. When a is not an integral value, $b < a$. Combining both, $b \leq a$.

By definition of the floor function, we also know a is strictly less than $\lfloor a\rfloor + 1$. Subtracting 1 from both sides yields, $a - 1 < \lfloor a\rfloor$. Because of the initial condition, this means $a - 1 < b$. Combining both inequalities gives $a - 1 < b \leq a$. Therefore,

$$\lfloor a\rfloor = b \implies a - 1 < b \leq a. \tag{12}$$

Now, let us prove the converse, if $a - 1 < b \leq a$, then $\lfloor a\rfloor = b$.

Let $a - 1 < b \leq a$. The floor of a real number is greater than or equal to an integer if and only if that real number is greater than or equal to that integer, or $\lfloor a\rfloor \geq b \iff a \geq b$. Therefore, from $b \leq a$, we get $b \leq \lfloor a\rfloor$.

Adding 1 to both sides of $a - 1 < b$ gives $a < b + 1$. A real number is less than an integer if and only if the floor of that real number is also less than the integer. Therefore, $\lfloor a\rfloor < b + 1$. We also know that for any two integers c and d, $c < d + 1$ if and only if $c \leq d$. Therefore, because $\lfloor a\rfloor$ and b are integers, $\lfloor a\rfloor \leq b$. Combining $\lfloor a\rfloor \leq b$ and $b \leq \lfloor a\rfloor$, we get $b = \lfloor a\rfloor$. Therefore,

$$a - 1 < b \leq a \implies \lfloor a\rfloor = b. \tag{13}$$

Combining equations 12 and 13, $\lfloor a\rfloor = b \iff a - 1 < b \leq a$. ∎

Theorem 14. *The optimal strategy to Ebert's Hat Puzzle for n cats and 2 hat colors has* $p_{\text{win}} = \frac{1}{2^n}\left\lfloor\frac{n2^n}{n+1}\right\rfloor$.

Proof. Let x be the number of winning configurations. Because the number of winning configurations is equal to the number of correct guesses, and the number of correct guesses equals the number of incorrect guesses, the number of incorrect guesses is also equal to x. Further, because each losing configuration is only made up of incorrect

guesses and there are n cats, the number of losing combinations is between $\frac{x}{n}$ (if x is a multiple of n) and $\frac{x}{n} + 1$ (if x is not a multiple of n).

There are 2^n total possible configurations. Because there are x winning configurations, the number of losing configurations is $2^n - x$.

Combining both ways of calculating the total number of losing configurations gives:

$$\frac{x}{n} \le 2^n - x \le \frac{x}{n} + 1.$$

We can rearrange the inequality to be $\frac{n2^n - n}{n+1} \le x \le \frac{n2^n}{n+1}$. Looking at the term $\frac{n2^n - n}{n+1}$, we can separate the fraction yielding $\frac{n2^n}{n+1} - \frac{n}{n+1}$. By inspection, we can see that $\frac{n}{n+1}$ is always strictly less than 1, so $\frac{n2^n}{n+1} - \frac{n}{n+1}$ is strictly greater than $\frac{n2^n}{n+1} - 1$. Inserting this into the inequality including x, we get:

$$\frac{n2^n}{n+1} - 1 < \frac{n2^n - n}{n+1} \le x \le \frac{n2^n}{n+1}.$$

By applying equation 13, we know that $x = \left\lfloor \frac{n2^n}{n+1} \right\rfloor$. Furthermore, since x is the number of winning configurations, the optimal strategy's probability of winning is $p_{\text{win}} = \frac{x}{2^n}$, or

$$p_{\text{win}} = \frac{1}{2^n} \left\lfloor \frac{n2^n}{n+1} \right\rfloor. \tag{14}$$

∎

Theorem 15. *A Hamming code strategy with $n^* = 2^r - 1$ and $q = 2$ is an optimal strategy.*

Proof. Let us consider a Hamming code strategy with special case n^* where $n^* = 2^r - 1$ and $r \in \mathbb{N}$ per equation 11. Let us also consider optimal strategies where $p_{\text{win}} = \frac{1}{2^{n^*}} \left\lfloor \frac{n^* 2^{n^*}}{n^* + 1} \right\rfloor$ from equation 14 for the special case n^*.

Substituting $2^r - 1$ for n^* in the denominator inside the floor yields $p_{\text{win}} = \frac{1}{2^{n^*}} \left\lfloor \frac{n^* 2^{n^*}}{2^r} \right\rfloor$. This is equal to $\frac{1}{2^{n^*}} \left\lfloor n^* \cdot 2^{n^* - r} \right\rfloor$ via the properties of exponents. Furthermore, since n^* and r are natural numbers and $n^* \ge r$, the expression held within the floor function is an integer. Therefore, $p_{\text{win}} = \frac{1}{2^{n^*}} \cdot \frac{n^* 2^{n^*}}{n^* + 1}$, which simplifies to

$$p_{\text{win}} = \frac{n^*}{n^* + 1}. \tag{15}$$

Since the optimal strategy's probability of winning from equation 15 equals that calculated for the perfect Hamming code strategy in equation 10, we can say any Hamming code strategy with $n^* = 2^r - 1$ for the case $q = 2$ is an optimal strategy.

∎

4. Ebert's Hat Puzzle with Three Cats ($n = 3$) and Three Hat Colors ($q = 3$), Extended to the General Case of n Cats and q Hat Colors

We have looked at the puzzle when the hat colors are binary. Now, let Ebert's Hat Puzzle be the same, but instead of only black-banded hats (B) and red-banded hats

(R), suppose there are also green-banded hats (G), as illustrated in figure 6. All hat colors are chosen randomly and independent of each other. Does this change the probability of winning? Does this change the optimal strategy? Regardless, the overall goal remains the same:

   Goal: Come up with a strategy that will allow the n cats to escape with high probability, meaning the probability of winning, $p_{\text{win}} \to 1$ as $n \to \infty$.

Figure 6. *Ebert's Hat Puzzle with three colors, as experienced by Buttons (left), Mittens (center), and Whiskers (right).*

   Before we start trying to solve these questions, we must redefine $d_i(u,v)$ from equation 1 since for cases where digits are not binary, $|u_i - v_i|$ will not necessarily result in 1 when $u_i \neq v_i$, although for non-binary digits, $|u_i - v_i|$ is still 0 when $u_i = v_i$. Since a Hamming distance only cares if two bits are different, not the value, we can redefine equation 1 as:

$$d_i(u,v) = \begin{cases} 0 & \text{if } u_i = v_i \\ 1 & \text{if } u_i \neq v_i. \end{cases} \tag{1'}$$

   With only minor revisions to the proofs, it should be clear that the Hamming distance properties HP1 through HP4 still hold.

   We will now revisit the strategies used to solve Ebert's Hat Puzzle with two colors. However, this time we will generalize them to q colors and then calculate the results for $q = 3$.

4.1. Strategy 1: *Each cat randomly guesses the color of their hat*

Because there are now q colors, the chance of each cat guessing correctly is $\frac{1}{q}$. This means if each cat guesses a color randomly, the overall probability of winning is $p_{\text{win}} = \left(\frac{1}{q}\right)^n$.

   For Ebert's Hat Puzzle as presented in this paper with 3 cats and 3 hat colors, the probability that Buttons, Mittens, and Whiskers will escape using Strategy 1 is $p_{\text{win}} = \left(\frac{1}{3}\right)^3 = \frac{1}{27} = 0.037$.

4.2. Strategy 2: *Each cat randomly passes or guesses the color of their hat*

If each cat randomly guesses a color or passes, similar to before, the denominator will be $(q + 1)^n$ because each cat has $q + 1$ options to choose from (the number of colors plus 'pass'). The numerator does not change since it depends on the number of cats who pass rather than the number of hat colors.

   Using the configuration in figure 6 as an example, when none of the cats pass, there is still $\binom{3}{3} = 1$ configuration for a win (RBG). Similarly, when one cat passes,

there are still $\binom{3}{2}$ configurations that will win (PBG, RPG, and RBP), and when 2 cats pass, there are still $\binom{3}{1}$ winning configurations (PPG, PBP, and RPP). As before, with i passes for n cats, there are $\binom{n}{n-i}$ winning configurations. When every cat passes, as stated in the puzzle rules, they still all lose. Therefore, summing the total number of winning configurations (the numerator) results in $\sum_{i=1}^{n}\binom{n}{n-i}$. As before, this can be further simplified to $2^n - 1$ by applying equation 9. Dividing the total number of winning configurations by the total number of configurations gives

$$p_{\text{win}} = \frac{2^n - 1}{(q+1)^n}.$$

For Ebert's Hat Puzzle as presented in this paper with 3 cats and 3 hat colors, the probability that Buttons, Mittens, and Whiskers will escape using Strategy 2 is $p_{\text{win}} = \frac{2^3 - 1}{(3+1)^3} = \frac{7}{64} = 0.109$, a significant increase from Strategy 1.

4.3. Strategy 3: *One cat randomly guesses the color of their hat while the other cats pass*

As with the case of two colors, because each cat has a $\frac{1}{q}$ chance of being correct, all cats collectively also have a $\frac{1}{q}$ chance of winning if only one of them chooses and the others all pass.

For Ebert's Hat Puzzle as presented in this paper with 3 cats and 3 hat colors, the probability that Buttons, Mittens, and Whiskers will escape using Strategy 3 is $p_{\text{win}} = \frac{1}{3} = 0.333$, which again shows a significant increase from both Strategies 1 and 2.

4.4. Strategy 4: *Each cat guesses the color of their hat or passes, depending on the color of the other cats' hats*

As explained in the two-color hat scenario, using a Hamming code strategy only works for special values of n^* that correspond to *perfect* Hamming codes of n^* binary digits. Similarly, there are special values of n^* for q-value digits as well.

Theorem 16. *Perfect Hamming codes only exist for special values of n^* and q when $n^* = \frac{q^r - 1}{q - 1}$ where $r \in \mathbb{N}$.*

Proof. Let u be a codeword in code $\mathbb{C}$. Unlike the previous derivation in Theorem 12, in this case the neighborhood around u is more complicated, as illustrated in figure 7. The set of all nearby non-codewords $\mathbb{W}$ is itself made up of multiple $(q-1)$-cliques w_i. Each $(q-1)$-clique w_i is, in turn, made up of all words where the ith digit can be any possible value except for the digit value that changes the word into u. There are n cliques of size $q-1$ per codeword. Therefore, each codeword is connected to $(q-1)n$ non-codewords. Notably, $w_i \cup u$ forms a q-clique with all words where the ith digit can be any possible value.

Following the same logic as Theorem 12, for the Strategy 4 Hamming code solution to work for an arbitrary n and q, each possible configuration must be a codeword (losing configuration) or a non-codeword (potential winning configuration). Furthermore, each winning configuration must be one bit change away from one and only one codeword.

Given n cats and q hat colors, there are q^n possible hat configurations. Within those configurations, let us assume there are q^x codewords where $x \leq n$. Because each codeword is connected to $(q-1)n$ non-codewords, there must be $(q-1)nq^x$ non-codewords. Adding all the codewords and non-codewords together, we get a total of $q^x + (q-1)nq^x$ words $= q^n$ total possible configurations.

We leave it to the reader to continue the proof in the same way as Theorem 12. The general result is that for n cats and q hat colors, a Hamming code can only be perfect for special cases of $n = n^*$ when

$$n^* = \frac{q^r - 1}{q - 1} \qquad (16)$$

where $r \in \mathbb{N}$.

∎
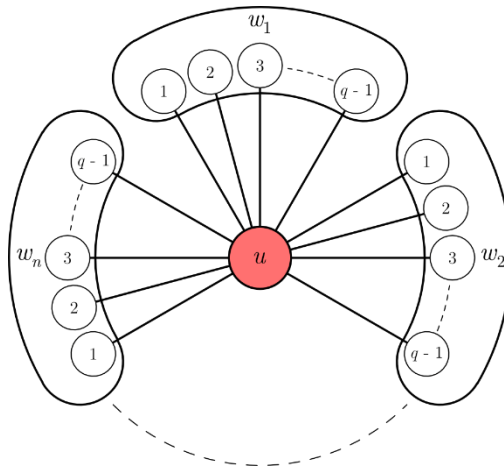
Figure 7. *Graph showing the n cliques of size $q-1$ made up of w_1 through $w_n \in \mathbb{W}$ connected to codeword $u \in \mathbb{C}$.*

Theorem 17. *A perfect Hamming code with n^* digits of q values each that works for Strategy 4 has $p_{\text{win}} = \frac{n^*}{(q-1)n^* + 1}$.*

Proof. Let q be the number of hat colors, n^* be the number of cats that meets the requirements of equation 16, and u be a codeword in code $\mathbb{C}$.

Each change in a configuration's digit can go to $q-1$ other different values. Because of this, we know that each digit change makes a q-clique. There are also n^* unique digits in codeword u. Therefore, u is part of n unique q-cliques. Pulling u outside each of the q-cliques results in a central vertex u surrounded by n^* cliques of size $q-1$ as illustrated in figure 7.

As proven before, the neighborhood of u is exactly the same as all other codeword neighborhoods, and no vertex is in two codeword neighborhoods. Therefore, by looking at a single neighborhood, we get the probability of the whole graph. Because there are $(q-1)n^*$ non-codewords and $(q-1)n^* + 1$ total words (including u), the probability of being on a non-codeword configuration is $\frac{(q-1)n^*}{(q-1)n^* + 1}$. Furthermore, there are $q-1$ possible hat colors within each $(q-1)$-clique, ignoring the color that represents codeword u, so within each non-codeword clique, a cat has a

$\frac{1}{q-1}$ chance of choosing the correct color, resulting in a winning configuration.

Therefore,

$$p_{\text{win}} = \frac{(q-1)n^*}{(q-1)n^*+1} \cdot \frac{1}{q-1} = \frac{n^*}{(q-1)n^*+1}. \tag{17}$$

■

The astute reader will note there is no perfect Hamming code for the case $n = 3$ when $q = 3$. This is illustrated in table 2. Unfortunately, this means there is no possible optimal Hamming code solution to the case of three cats with three hat colors. However, there still exist strategies better than the probabilistic strategies 1 through 3. Specifically, Guo et al. performed a numerical analysis of all possible ($4^9 = 262,144$) symmetric strategies and found the best case that could be translated into a relatively simple set of rules, paraphrased as follows [1]:

- Assign a primary hat color (black-banded) and a secondary hat color (red-banded).
- Any cat that sees two hats of the primary color will choose the secondary color.
- Any cat that sees only one hat of the primary color will pass.
- Any cat that sees no hats of the primary color will choose the primary color.

Table 2. *Values of n^* for various q that meet the conditions of equation 16: $n^* = \frac{q^r-1}{q-1}$.*

r	n^* ($q = 2$)	n^* ($q = 3$)	$\cdots$
1	1	7	$\cdots$
2	3	4	$\cdots$
3	7	13	$\cdots$
4	15	40	$\cdots$
5	31	121	$\cdots$
$\vdots$	$\vdots$	$\vdots$	$\ddots$

In table 3, we can see that when applying these rules to all hat permutations, the cats each guess correctly five times and incorrectly ten times, but collectively win $\frac{15}{27}$ times overall, which is a significant improvement over the probabilistic strategies.

Parallel to the case of two hat colors, an important feature of the results shown in table 3 is that for three hat colors, there are now twice as many incorrect guesses as correct guesses. Again, this makes sense when viewed through the lens of cat i. Regardless of what the other cats' hat colors are, cat i will have equal likelihood of wearing a black-banded hat, a red-banded hat, or a green-banded hat, with the probability of $\frac{1}{3}$ each. Thus, whenever cat i guesses, they will be correct a third of the time.

Unlike the case of two hat colors, however, table 3 shows that while each winning configuration consists of a single correct guess and two passes, in this case, the losing configurations are not all packed with incorrect guesses. More specifically, while nine of the losing configurations are made up of three incorrect guesses each (fully packed), three of the losing configurations are made up of a single incorrect

guess with two passes.

While there is no perfect Hamming code for the case $n = 3$ when $q = 3$, equation 16 and table 2 show there *is* a perfect Hamming code for the case $n = 4$ and $q = 3$ when $r = 2$. Next, we will try to apply the Hamming code strategy to that case and see the resultant probability of winning. Of note, finding the codewords for the situation of larger n and for $q > 2$ is not as trivial is it was for the case of $n = 3$ and $q = 2$ (remember, in this case the set of codewords $\mathbb{C} = \{BBB, RRR\}$). A description of how to determine the codewords for arbitrary n and q is beyond the scope of this paper but can be found in MacWilliams and Sloane [7], as well as in multiple other texts that describe Linear codes and Hamming codes. For the specific case of $n = 4$ and $q = 3$, there are multiple possible sets of codewords that meet the requirements $\delta = 3$ and the distance between any non-codeword w and any other codeword u is $d(w, u) = 1$. One possible set of codewords using the approach of MacWilliams and Sloane is $\mathbb{C} = \{BBBB, BRRR, BGGG, RBRG, RRGB, RGBR, GBGR, GRBG, GGRB\}$.

Table 3. *All possible three-color hat combinations ($q = 3$) for the case $n = 3$, along with guesses and overall outcomes from applying Guo et al.'s best-case strategy. B indicates a black-banded hat, R indicates a red-banded hat, G indicates a green-banded hat, and P indicates a pass. Each correct guess is marked with a check (✓), and each incorrect guess is marked with a cross (×).*

Buttons' Hat	Mittens' Hat	Whiskers' Hat	Buttons' Guess	Mittens' Guess	Whiskers' Guess	Outcome
B	B	B	R (×)	R (×)	R (×)	Loss
B	B	R	P ( )	P ( )	R (✓)	Win
B	B	G	P ( )	P ( )	R (×)	Loss
B	R	B	P ( )	R (✓)	P ( )	Win
B	R	R	B (✓)	P ( )	P ( )	Win
B	R	G	B (✓)	P ( )	P ( )	Win
B	G	B	P ( )	R (×)	P ( )	Loss
B	G	R	B (✓)	P ( )	P ( )	Win
B	G	G	B (✓)	P ( )	P ( )	Win
R	B	B	R (✓)	P ( )	P ( )	Win
R	B	R	P ( )	B (✓)	P ( )	Win
R	B	G	P ( )	B (✓)	P ( )	Win
R	R	B	P ( )	P ( )	B (✓)	Win
R	R	R	B (×)	B (×)	B (×)	Loss
R	R	G	B (×)	B (×)	B (×)	Loss
R	G	B	P ( )	P ( )	B (✓)	Win
R	G	R	B (×)	B (×)	B (×)	Loss
R	G	G	B (×)	B (×)	B (×)	Loss
G	B	B	R (×)	P ( )	P ( )	Loss
G	B	R	P ( )	B (✓)	P ( )	Win
G	B	G	P ( )	B (✓)	P ( )	Win
G	R	B	P ( )	P ( )	B (✓)	Win
G	R	R	B (×)	B (×)	B (×)	Loss
G	R	G	B (×)	B (×)	B (×)	Loss
G	G	B	P ( )	P ( )	B (✓)	Win
G	G	R	B (×)	B (×)	B (×)	Loss
G	G	G	B (×)	B (×)	B (×)	Loss

As with Guo et al.'s strategy for $n = 3$ and $q = 3$, we must employ a set of rules that accommodates more than two hat colors. One potential set of rules could be

as follows (parallel to the rules used with Strategy 4 in the 2-hat-color case):

- Assign a primary hat color (black-banded), a secondary hat color (red-banded), and a tertiary hat color (green-banded).
- Any cat who sees the possibility of an adjacent codeword will choose a different color to ensure a codeword *is not* formed. In this case, since there are two different colors to choose, if they see primary hat colors, they will choose the secondary hat color; if they see secondary hat colors; they will choose the tertiary hat color; and if they see tertiary hat colors, they will choose the primary hat color. Said another way, if a cat sees BB, they will choose R; if they see RR, they will choose G; and if they see GG, they will choose B.
- Any cat who cannot see the possibility of an adjacent codeword will pass. In this case, if a cat sees BR, BG, or RG, they cannot determine which codeword is adjacent, and there is not enough information to make an informed guess, so they pass.

Since there are now $q^{n^*} = 3^4 = 81$ possible configurations, it is impractical to list them all as with table 3. However, it can easily be determined by listing all combinations that using these rules, $p_{\text{win}} = \frac{36}{81} = 0.444$. There are multiple other rule sets that can be applied with similar results. Equation 17 indicates the probability of winning should be $p_{win} = \frac{n^*}{(q-1)n^*+1} = \frac{4}{(3-1)4+1} = \frac{4}{9} = 0.444$ which matches this result, indicating these rules give the maximum probability of winning when using the Hamming code strategy.

For Ebert's Hat Puzzle as presented in this paper with 3 cats and 3 hat colors using Guo et al.'s set of rules, the probability that Buttons, Mittens, and Whiskers will escape using Strategy 4 is $p_{\text{win}} = \frac{15}{27} = 0.556$.

For the case of 4 cats and 3 hat colors using the Hamming code method, the probability that Buttons, Mittens, and Whiskers will escape using Strategy 4 is $p_{\text{win}} = \frac{36}{81} = 0.444$.

4.5. The optimal strategy for q hat colors

Theorem 18. *The optimal strategy to Ebert's Hat Puzzle for n cats and q hat colors has* $p_{win} = \frac{q-1}{q^n} \left\lfloor \frac{nq^n}{(n+q-1)(q-1)} \right\rfloor$.

Proof. Similar to the case of two hat colors, there are three properties required for an optimal strategy, amended slightly for an arbitrary number of hat colors:

1. In an optimal winning configuration, only one cat guesses correctly and the other cats pass.
2. In an optimal losing configuration, as many incorrect guesses are packed into as few configurations as possible.
3. The total number of incorrect guesses is equal to $q - 1$ times the total number of correct guesses.

Extending the logic of Theorem 14 to n cats and q hat colors, let x be the number of winning configurations. Because the number of winning configurations is equal to the number of correct guesses, and the number of incorrect guesses equals $q - 1$ times the number of correct guesses, the number of incorrect guesses is equal to $(q - 1)x$. Unlike the case of two hat colors, with q hat colors it is no longer a valid assumption that the incorrect guesses are all fully packed into losing configurations.

However, we can still state the number of losing combinations is between $\frac{(q-1)x}{n}$ (if $(q-1)x$ is a multiple of n) and $\frac{(q-1)x}{n} + (q-1)$ (if $(q-1)x$ is not a multiple of n).

There are now q^n total possible configurations. Because there are x winning configurations, the number of losing configurations is $q^n - x$.

Combining both ways of calculating the total number of losing configurations gives

$$\frac{(q-1)x}{n} \leq q^n - x \leq \frac{(q-1)x}{n} + (q-1).$$

Multiplying by n and dividing by $(q-1)$ yields $x \leq \frac{nq^n - nx}{q-1} \leq x + n$. Rearranging the values to consolidate the terms containing x gives $\frac{nq^n}{q-1} - n \leq \frac{n}{q-1}x + x \leq \frac{nq^n}{q-1}$. We can rewrite the center expression to $\frac{n+q-1}{q-1}x$. Isolating for $\frac{x}{q-1}$, gives

$$\frac{1}{n+q-1}\left(\frac{nq^n}{q-1} - n\right) \leq \frac{x}{q-1} \leq \frac{nq^n}{(n+q-1)(q-1)}. \tag{18}$$

Looking at the term $\frac{1}{n+q-1}\left(\frac{nq^n}{q-1} - n\right)$, we can multiply through, yielding $\frac{nq^n}{(n+q-1)(q-1)} - \frac{n}{n+q-1}$. By inspection, we can see that $\frac{n}{n+q-1}$ is always strictly less than 1, so we can say

$$\frac{nq^n}{(n+q-1)(q-1)} - 1 < \frac{nq^n}{(n+q-1)(q-1)} - \frac{n}{n+q-1}.$$

Combining with equation 18 gives

$$\frac{nq^n}{(n+q-1)(q-1)} - 1 < \frac{1}{n+q-1}\left(\frac{nq^n}{q-1} - n\right) \leq \frac{x}{q-1} \leq \frac{nq^n}{(n+q-1)(q-1)}.$$

By applying equation 13, we know that $\frac{x}{q-1} = \left\lfloor \frac{nq^n}{(n+q-1)(q-1)} \right\rfloor$. Therefore, the number of winning configurations $x = (q-1)\left\lfloor \frac{nq^n}{(n+q-1)(q-1)} \right\rfloor$ and the optimal strategy's probability of winning is $p_{\text{win}} = \frac{x}{q^n}$, or

$$p_{\text{win}} = \frac{q-1}{q^n}\left\lfloor \frac{nq^n}{(n+q-1)(q-1)} \right\rfloor. \tag{19}$$

∎

From equation 19, we find p_{win} for the case $n = 3$ and $q = 3$ to be $\frac{3-1}{3^3}\left\lfloor \frac{3 \cdot 3^3}{(3+3-1)(3-1)} \right\rfloor = \frac{2}{27}\left\lfloor \frac{81}{10} \right\rfloor = \frac{16}{27}$. By inspection, this is the same as saying the optimal strategy has 16 wins out of a total of 27 configurations. By contrast, as shown previously, Guo et al.'s strategy results in 15 wins. With respect to Guo et al., their assertion that "this is an optimal strategy among all symmetric strategies [and] indeed optimal among all strategies" [1] is not correct. While their strategy may be the best of those they numerically analyzed, and in fact may be the best achievable symmetric strategy for the case $n = 3$ with $q = 3$, it is not an "optimal" strategy as defined in this paper.

5. Summary of Results

All of the results of the various strategies, as well as the optimal strategy, for the cases of n cats and q hat colors, along with specific results for the cases explored in this paper, are summarized in table 4. Table 5 looks at the asymptotic limits for p_{win} as

$n \to \infty$ and as $q \to \infty$. As a reminder, our stated goal in this paper was to identify strategies that allow the n cats to escape with high probability, meaning $p_{win} \to 1$ as $n \to \infty$. The results in table 5 show this is only possible for the Hamming code strategy in the case of two hat colors ($q = 2$). For three or more hat colors, the cats cannot escape with high probability, although optimal strategies may exist that have yet to be discovered.

Table 4. *Summary of p_{win} results for each strategy for a given n and q.*

Strategy	p_{win}	$n = 3,$ $q = 2$	$n = 3,$ $q = 3$	$n = 4,$ $q = 3$
1: Random	$\left(\dfrac{1}{q}\right)^n$	$\dfrac{1}{8} = 0.125$	$\dfrac{1}{27} = 0.037$	$\dfrac{1}{81} = 0.012$
2: Random + Pass	$\dfrac{2^n - 1}{(q + 1)^n}$	$\dfrac{7}{27} = 0.259$	$\dfrac{7}{64} = 0.109$	$\dfrac{15}{256} = 0.059$
3: 1 Guess + $(n - 1)$ Passes	$\dfrac{1}{q}$	$\dfrac{1}{2} = 0.5$	$\dfrac{1}{3} = 0.333$	$\dfrac{1}{3} = 0.333$
4a: Hamming Code[1]	$\dfrac{n^*}{(q - 1)n^* + 1}$	$(r = 2)$ $\dfrac{3}{4} = 0.75$	-	$(r = 2)$ $\dfrac{4}{9} = 0.444$
4b: Guo et al.	-	-	$\dfrac{15}{27} = 0.556$	-
Optimal	$\dfrac{q - 1}{q^n}\left\lfloor\dfrac{nq^n}{(n + q - 1)(q - 1)}\right\rfloor$	$\dfrac{1}{8}\lfloor 6\rfloor = \dfrac{6}{8}$ $= 0.75$	$\dfrac{2}{27}\left\lfloor\dfrac{81}{10}\right\rfloor = \dfrac{16}{27}$ $= 0.593$	$\dfrac{2}{81}\lfloor 27\rfloor = \dfrac{54}{81}$ $= 0.667$

[1]Only applicable for values of $n^* = \dfrac{q^r - 1}{q - 1}$ where $r \in \mathbb{N}$. For these cases, the corresponding value of r is indicated in the table.

Table 5. *Asymptotic limits of p_{win} for each strategy with respect to n and q.*

Strategy	p_{win}	$\lim n \to \infty$	$\lim q \to \infty$
1: Random	$\left(\dfrac{1}{q}\right)^n$	0	0
2: Random + Pass	$\dfrac{2^n - 1}{(q + 1)^n}$	0	0
3: 1 Guess + $(n - 1)$ Passes	$\dfrac{1}{q}$	$\dfrac{1}{q}$	0
4a: Hamming Code	$\dfrac{n^*}{(q - 1)n^* + 1}$	$\dfrac{1}{q - 1}$	0
4b: Guo et al.	-	-	-
Optimal	$\dfrac{q - 1}{q^n}\left\lfloor\dfrac{nq^n}{(n + q - 1)(q - 1)}\right\rfloor$	1	0

6. Conclusion

As seen in this paper, Hamming codes have applications in seemingly unrelated topics. Taking a thought puzzle with low probabilistic chance of winning and using Hamming codes, we are able to increase the chance of winning drastically. We showed that in certain cases, this can result in a solution with high probability, which is not possible with probabilistic solutions alone. We exhaustively explored the scenario of 3 cats and 2 hat colors and proved that the Hamming code strategy is optimal. We then extended the analysis to the general situation of n cats and q hat colors. We showed that the general Hamming code strategy, while better than probabilistic, applies only to specific values of n and is not optimal for $q > 2$ hat colors.

This paper has a number of logical continuations that interest the author and could be the subject of future research. How would these strategies change if the probability of choosing one color hat differed from another? Can the probability of winning be increased if we look at more asymmetric strategies with each cat following a different predetermined set of rules? Can numerical analysis be applied to some of the larger $n > 3$ and $q > 3$ scenarios to determine new and interesting strategies? Computing power has certainly increased significantly since Ebert first posed the puzzle in 1998 and Guo et al. published their computational results in 2006. What happens if the rules of the game are changed, such as by allowing sub-groups of cats to discuss rules beforehand, but not letting the overall group discuss collectively? How can turn-based strategies be applied, incorporating iterative strategies and other game theory concepts? Are there ways to cheat using techniques that are technically within the rules and can increase p_{win}, but were certainly not intended?

7. Afterword

Luckily, Buttons, Mittens, and Whiskers were all close friends with Richard Hamming's cat, Tabby. They often discussed Hamming's musings and were especially interested in mathematics and the new field of computers. Buttons had been thinking about Hamming's error detection and correction discovery all day, which is probably why they got caught in such an obvious trap in the first place. However, Buttons, being the smartest cat of the group, applied the Hamming code strategy to increase their probability of escape to 75%. Did they survive? We're glad to share that Buttons, Mittens, and Whiskers are still alive today, continuing their pursuit of mathematical knowledge... and wearing hats.

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An In(Queer)y Into Title VII:
How *Bostock v. Clayton County* Fails Bisexual and Nonbinary Employees

Jeremy Tu

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Abstract

In *Bostock v. Clayton County*, the Supreme Court ruled that Title VII protects gay and transgender workers from employment discrimination. Despite being hailed as a victory for LGBTQ+ rights, this paper examines the implications of the Bostock ruling from a queer legal theory perspective, emphasizing the potential exclusion of bisexual and nonbinary employees from protections against employment discrimination. This paper examines the current state of bisexual employment protections (or lack thereof) under Title VII as a precursor to discuss the potential future of nonbinary employment protections. Drawing upon Damir Banović's second framework of queer legal theory, this paper critically analyzes the ways in which the majority opinion in *Bostock v. Clayton County*, Justice Alito's dissent, and Title VII discrimination law reinforce the gender binary, adopting a 'queering' perspective. By exploring how Bostock's reliance on a gender binary effectively excludes nonbinary individuals from Title VII employment protections, this paper hopes to uncover the problematic consequences of erasing bisexual and nonbinary experiences and perpetuating hierarchies that disadvantage these identities. Through this analysis, this paper underscores how these outcomes diminish the transformative potential of the Bostock ruling. Finally, this paper concludes by offering suggestions for a queer-inclusive majority opinion and makes recommendations for activists, the LGBTQ+ community, and civil-rights lawyers to move towards a queer-inclusive future.

Introduction

On November 9, 2021, Brie Boyle filed a lawsuit against their employer, Starbucks Corporation, after two supervisors led a targeted campaign of sexual harassment and gender discrimination. Boyle told their colleagues of their plan to transition from male to nonbinary gender status and wished for their colleagues to respect their gender identity. They claimed that their supervisors continued to use male pronouns, telling

Boyle to "man up" (Dean, 2021, para. 3). Their supervisors also learned of Boyle's bisexuality with the lawsuit claiming:

> From the moment information concerning Plaintiff's gender and sexual orientation became known to their co-workers and management, Plaintiff was forced to deal with insults and mistreatment nearly every time Plaintiff worked a shift between November of 2019 and May of 2020 (*Boyle v. Starbucks Corporation*, n.d., p. 2).

A year prior, the Supreme Court of the United States ruled in *Bostock v. Clayton County* (2020) that Title VII of the Civil Rights Act of 1964 protected members of the LGBTQ+ community from employment discrimination. *Bostock* was lauded as highly progressive and a gargantuan step for LGBTQ+ rights by legal scholars, lawyers, and media alike. Kristen Browde, the co-chair of the National Trans Bar Association, described the ruling to NBC News as "every bit as significant, if not more so, than the marriage equality decision" (Moreau, 2020, para. 5), referring to *Obergefell v. Hodges* (2015) which legalized same-sex marriage. The director of the ACLU's LGBTQ & HIV Project, James Esseks, concurred by saying, "This is a huge victory for LGBTQ equality" (Browning, 2020, para. 10).

However, are bisexual and nonbinary employees, like Brie Boyle, thoroughly protected from employment discrimination based on their identity? Does *Bostock* provide a solid foundation for discrimination suits for the numerous bisexual and nonbinary individuals who face employment discrimination?

Through an analysis of queer legal theory, this paper argues that *Bostock* leaves gaps in protections for those who belong to the 'B' and '+' of the LGBTQ+ community and fails to live up to its reputation as being a "huge victory for LGBTQ equality" (Browning, 2020, para. 10), leaving the rights of bisexual and nonbinary employees vulnerable to heinous employment discrimination. By capitalizing on queer theory's antinormative, disruptive nature and contrasting it with the law's normative, rigid applications, this paper uses queer theory to question this seemingly 'pro-LGBTQ+' court case and subvert the Supreme Court's assumptions of LGBTQ+ people, their identities, and socially constructed hierarchies.

Background and Methodology

Sex, Gender, and the Gender Binary

To understand Title VII and the *Bostock* decision, key terms used in the decision and in this paper must be defined.

Although commonly used interchangeably, sex (biological) and gender (identity) are not synonyms. Biological sex refers to a person's physical and physiological traits, including chromosomal makeup and reproductive anatomy (Tseng, 2008). The presence of either XX or XY chromosomes typically determines biological sex, leading to the notion of a sex binary: male or female. However, not everyone is born within this binary. Some scholars disagree with the identification of binaries to describe human characteristics including sex (Fuentes, 2023) as combinations of chromosomal arrangements exist outside of XX and XY, like XXY (Mayo Clinic, n.d.) and XYY (Sood & Clemente Fuentes, 2023). Individuals that have one of these conditions of sexual development are intersex, with some estimates suggesting it affects one in every two thousand people (Hughes et al., 2007).

In contrast, gender refers to non-physical roles, norms, and behaviors based on societal assumptions of men and women. Gender identity refers to the personal relationship everyone has towards gender, masculinity, and femininity (Tseng 2008).

Gender may manifest incongruently with a person's biological sex, such as someone who is assigned male at birth due to the presence of male genitalia and raised in accordance with the societal expectations of a man but who no longer identifies as a man (American Psychological Association, 2018). People who do not identify with the sex they were assigned at birth are transgender, and those who do identify with the sex they are assigned at birth are cisgender (American Psychological Association, 2018). Binary transgender individuals refer to those who identify as a gender that is different from the sex they were assigned at birth and specifically identify within the male-female binary (e.g., transgender men and transgender women) (Anderson, 2023).

The gender binary assumes that every individual's gender can be categorized as either male or female. However, some individuals identify outside of a strict gender binary and identify as non-binary, with their gender identity being neither male nor female (Bouman et al., 2016), while others may be gender-fluid and experience gender as dynamic (Harvard Health, n.d.). Gender identities outside of the bounds of a strict binary have existed across various time periods and cultural contexts such as the Hijra in India (Harvard Divinity School, 2018) and two-spirit Indigenous peoples (Indian Health Service, n.d.), with some scholars interpreting gender's resistance towards being fixed as gender being a spectrum rather than a binary. Although many sociological features and legal precedents can be understood as sustaining the gender binary, bisexuality should not be understood as presupposing an existence of a gender binary because bisexual individuals commonly describe their attraction in both binary and nonbinary terms (Galupo et al., 2017). These words serve as tools in queer legal theorists' tool kits to question how normative structures, like the government, maintain hierarchies that subjugate sexual and gender minorities.

Queer (Legal) Theory

Queer theory as a field is definitionally unstable. Similar to the colloquial definition of queer as 'weird' and resistant to labels, queer theory and practice are "focused on boundary-pushing rather than boundary-setting; contesting identities rather than establishing them; transgressing rather than institutionalizing social norms" (Lamble, 2021, p. 53). Involving various forms of study and critical questioning, queer theory "interrogate[s] social processes of normalization," questions forms of legal governance, and seeks to question the ways in which law regulates 'good' and 'bad' sexual subjects and practices (Lamble, 2021, p. 55). Rather than focus on a field or specific subject, such as LGBTQ+ populations, queer theory is "an approach or way of doing critique" (Lamble, 2021, p. 56), with one method, including questioning the norms of gender and sexuality. Queer theory broadly refers to 'queer' as a practice or method of interrogating normative structures and the government (Bohmer & Briggs, 1991). For example, some queer theorists are skeptical about the legalization of same-sex marriage due to the view that governmental recognition of certain LGBTQ+ people creates respectable queerness (Joshi, 2021), othering and policing certain queer identities. Queer theory can serve as a method to interrogate the true emancipatory potential of pro-LGBTQ+ legislation and question whether these methods of governance reinforce oppressive hierarchies and privilege certain queer bodies over others.

Due to queer theory's fluid nature, it may seem hard to pin down, use as an analytic to map out legal precedent, and traverse the law's strict boundaries and applications. However, it is because of the destabilizing nature of queer theory that it can 'queer' governance and question how the government ignores the variability of sex, gender, and sexual orientation (The Bridge, n.d.). Queer theory's application to

law is pluralistic with multiple varying frameworks and methods. Assistant Professor Damir Banović (2022) details three conceptual frameworks to queer legal theory: methods motivated to promote egalitarianism through expanding and changing the law in order to grant LGBTQ+ people the same rights as their heterosexual, cisgender counterparts; methods that critique law "from the inside" by pointing out how legal systems leave out sexual and gender minorities; and methods that view gender and sexual identities as flux and interrogate laws that seek to eliminate identities outside of "binary concepts of sexuality and gender" (pp. 2-3). Prior to investigating the peculiar relationship between queer theory's antinormativity and employment discrimination law's normativity, a background of Title VII must be given.

The Civil Rights Act and Title VII

The Civil Rights Act of 1964 was passed by Congress on July 2, 1964, and was signed into law by President Lyndon Johnson in response to resistance against racial desegregation in the United States (U.S. Department of Labor, n.d.). Title VII of the Civil Rights Act of 1964 outlaws employment discrimination "because of such individual's race, color, religion, sex, or national origin" (para. 149). However, discrimination based on sex was added to the bill by staunch civil rights opponent Congressman Howard Smith, who added the provision to Title VII as a wrecking amendment, attempting to sabotage the passage of the Civil Rights Act (Henry, 2014). Congress signed the bill with the addition of 'sex' into law without substantive debate on the amendment. Following the passage of the Civil Rights Act and Title VII, the courts contended whether Title VII's sex provision encompassed gender identity and sexual orientation. Fifty-six years later, the Supreme Court attempted to clarify this issue in *Bostock v. Clayton County*.

Bostock v. Clayton County

Bostock v. Clayton County was an amalgamation of several other cases and included *Altitude Express Inc. v. Zarda* and *G.R Harris Funeral Homes Inc. v. Equal Employment Opportunity Commission*. Gerard Bostock had worked in the Clayton County juvenile court system for ten years with a positive performance record. In 2013, he joined a gay recreational softball league, and his sexuality became known at his place of employment. Bostock received disparaging comments about his sexual orientation and was eventually fired for improper conduct during an internal audit of the funds he managed (*Bostock v. Clayton County*, 2020). Shortly following his termination, Bostock filed a suit of discrimination with the Equal Employment Opportunity Commission (EEOC). *Bostock v. Clayton County* and *Altitude Express Inc. v. Zarda* sought to answer whether Title VII protected against discrimination based on sexual orientation while *R.G. & G.R. Harris Funeral Homes Inc. v. Equal Employment Opportunity Commission* sought to answer whether transgender individuals were protected under Title VII.

In a 6-3 decision, the Supreme Court ruled on June 15, 2020, covering all three cases, that Title VII prohibited employment discrimination based on "homosexual or transgender" identity (*Bostock v. Clayton County*, 2020, p. 1737). Justice Neil Gorsuch led the majority opinion through an analysis of textualism, a method of statutory interpretation that views the law through its ordinary meaning without regard to the legislature's intent (*Bostock v. Clayton County*, 2020, p. 1737). Justice Gorsuch gave the example of a male and female employee, both of whom were attracted to men. If an employer fired a male employee for his attraction to men, Justice Gorsuch claimed "the employer discriminate[d] against him for traits or

actions it tolerate[d] in his female colleague," (*Bostock v. Clayton County*, 2020, p. 1741) and on the basis of the employee's sex as a man. Justice Gorsuch applied this to unlawful discrimination against transgender employees by saying if a transgender woman, who was identified as male at birth, was fired for traits or actions that the employer tolerates in a cis-gender woman, "sex plays an unmistakable and impermissible role" (*Bostock v. Clayton County*, 2020, p. 1742) which would constitute a Title VII violation. Justice Gorsuch succinctly wrote:

An employer who fired an individual for being homosexual or transgender fires that person for traits or actions it would not have questioned in members of a different sex. Sex plays a necessary and undisguisable role in the decision, exactly what Title VII forbids. (*Bostock v. Clayton County*, 2020, p. 1737)

Justice Gorsuch not only emphasized the relationship between sexual orientation and sex, but also that sex discrimination did not have to be a person's primary reason for termination; as long as the plaintiff can show that they would not have been terminated "but for" (*Bostock v. Clayton County*, 2020, p. 1742) their sex, they can pursue a Title VII suit.

Two dissents were authored by Justice Samuel Alito, joined by Justice Clarence Thomas, and Justice Brett Kavanaugh. In his dissent, Justice Alito noted that the ordinary meaning of 'sex' used by Congress in 1964 precluded sexual orientation or transgender status, as Congress did not have in mind gay and transgender people when adding the sex provision (*Bostock v. Clayton County*, 2020, p. 1749). Justice Alito noted:

When textualism is properly understood, it calls for an examination of the social context in which a statute was enacted because this may have an important bearing on what its words were understood to mean at the time of enactment. (*Bostock v. Clayton County*, 2020, p. 1767) Justice Alito criticized the majority opinion by further declaring:

There is only one word for what the Court has done today: legislation.... A more brazen abuse of our authority to interpret statutes is hard to recall. The Court tries to convince readers that it is merely enforcing the terms of the statute, but that is preposterous. (*Bostock v. Clayton County*, 2020, pp. 1755-1756)

Justice Kavanaugh penned his dissent by arguing that 'because of sex' does not include discrimination based on homosexuality because "In common parlance, Bostock and Zarda were fired because they were gay, not because they were men" (*Bostock v. Clayton County*, 2020, p. 1828). He later included in a footnote that this analysis would also apply to discrimination based on transgender status (*Bostock v. Clayton County,* 2020, p. 1823), saying transgender plaintiff Aimee Stephens was fired because she was transgender, not because of her sex. Justice Kavanaugh then points out the Court's history of not "stat[ing] or even hint[ing] that sexual orientation was just a form of sex discrimination" (*Bostock v. Clayton County*, 2020, p. 1833). Justice Kavanaugh later concurs with Justice Alito's opinion that the Court legislated from the bench as he "believe[s] that it was Congress's role, not this court's, to amend Title VII" (*Bostock v. Clayton County*, 2020, p. 1837).

Background and Methodology

Eight Million People Erased

Strikingly, the majority opinion fails to include or clarify the LGBTQ+ rights and protections at stake with the decision, seemingly reducing the stakes to just "the fate of a dangling participle" (McGinley et al., 2020, p. 12). By placing emphasis on the statutory term for sex and not addressing the LGBTQ+ workers who supposedly gained employment protections, Justice Gorsuch ignores the experiences of the roughly eight million lesbian, gay, bisexual, and transgender workers in the United States (Sears et al., 2021). Ironically, the only time millions of gay and lesbian workers are acknowledged is in Justice Kavanaugh's dissenting opinion, where he believes that the Court should not act to expand protections to them.

Furthermore, Justice Gorsuch's textualism sterilizes the stories and lived experiences of LGBTQ+ folks from *Bostock*. The majority opinion barely includes the three plaintiffs' experiences with discrimination as "[f]ew facts are needed to appreciate the legal question we face" (*Bostock v. Clayton County*, 2020, p. 1737). Pointedly, Justice Gorsuch leaves out the reason why Zarda had revealed his sexual orientation: he did not want his female client to feel uncomfortable while he was strapped to her during their skydiving session (*Bostock v. Clayton County*, 2020, p. 1738). By omitting this detail, Assistant Professor Jeremiah Ho points out how Justice Gorsuch sidesteps an analysis of gender roles that may have occurred based on Zarda's sex. "[F]rom enduring presumptions of heterosexuality as a male skydiving instructor with female clients [or] having standards of hetero-masculinity forced against him because of his known sexuality" (Ho, 2020, p. 21), these examples rooted in queer theory contour Zarda's discrimination suit and could have allowed for an investigation of heterosexism—how society privileges and views heterosexuality as the norm—and its causal relationship with homophobia. A majority opinion based on sex stereotyping could have allowed for this discussion, but Justice Gorsuch's textualism forgoes this potential.

Ignoring Sex Stereotyping

Justice Gorsuch's textualist analysis not only ignores the eight million LGBTQ+ workers in the United States, but the majority opinion does not include the story of Ann Hopkins and her case's precedence setting of sex stereotyping which numerous transgender plaintiffs have used to successfully win employment discrimination lawsuits.

Hopkins claimed accounting firm Price Waterhouse denied her partnership due to her lack of conformity to stereotypes based on her behavior and appearance. During her evaluation, Price Waterhouse partners described her as "macho," objected to her swearing "because it's a lady using foul language," and suggested she take "a course at charm school" (*Price Waterhouse v. Hopkins*, 1989, p. 236). Her head supervisor and mentor Thomas Beyer recommended that she "walk more femininely, talk more femininely, dress more femininely, wear make-up, have her hair styled, and wear jewelry" to improve her odds for partnership (*Price Waterhouse v. Hopkins*, 1989, p. 236). The Court observed that Hopkins' partnership denials were based on her resistance to conforming to stereotypes on how women should act, known as "sex stereotyping" (*Price Waterhouse v. Hopkins*, 1989, p. 236). The Supreme Court ruled in a 6-3 decision in *Price Waterhouse v. Hopkins* that Title VII's prohibition of sex discrimination additionally prohibits sex stereotyping, noting in the plurality decision

that "an employer who acts on the basis of a belief that a woman cannot be aggressive, or that she must not be, has acted on the basis of gender" (*Price Waterhouse v. Hopkins*, 1989, p. 250).

Price Waterhouse cemented sex stereotyping as employment discrimination and led to a number of lower courts ruling in favor of and served as a basis for numerous transgender plaintiffs' arguments. In a 2011 discrimination case, Vandy Beth Glenn, a transgender woman, told her employer, Georgia General Assembly, of her plans to transition from male to female and was fired shortly after. Judge Rosemary Barkett of the Eleventh Circuit Court of Appeals wrote for the unanimous decision that "A person is defined as transgender precisely because of the perception that his or her behavior transgresses gender stereotypes" (*Glenn v. Brumby*, 2011, p. 1317), and due to the predecent set by Price Waterhouse, this form of stereotyping was prohibited. The judge ruled in Glenn's favor and directly cited Price Waterhouse. The precedent of classifying sex stereotyping as a form of prohibited employment discrimination proved to serve as a basis for transgender plaintiffs to successfully file Title VII suits. However, *Bostock's* majority opinion fails to thoroughly discuss the rich history of the sex stereotyping cases that followed Price Waterhouse, only citing the case once (*Bostock v. Clayton County*, 2020, p. 1741). By favoring a textualist approach to interpret *Bostock* and sidestepping the productive litigation of Price Waterhouse and sex stereotyping, the majority opinion misses an opportunity to rigorously cement decades of protection from sex-based discrimination for transgender plaintiffs. The majority opinion also fails to protect bisexual and nonbinary workers from employment discrimination.

A Case Study of Bisexuality: A Glimpse Into the Future of Non-Binary Rights

Both bisexual and nonbinary identities disrupt binary concepts of sexual orientation and gender identity. Bisexuality troubles the Court's binary assumption of hetero/homosexuality, and nonbinary identities trouble the Court's binary assumption of man/woman. The Court fails to mention bisexual and nonbinary identities in its majority opinion and does not classify bisexual and nonbinary under the umbrella of "gay" and "transgender," which would have allowed for a more robust protection of their identities. By analyzing the ways in which *Bostock* fails to protect bisexual individuals from employment discrimination, the future of nonbinary protections appears.

Justice Gorsuch's textualist reading of Title VII's 'because of sex' statute problematizes the notion of *Bostock* as revolutionary in expanding employment protections for LGBTQ+ people when those who identify outside of the "L," "G," and (some) "T" may not be protected. *Bost*ock specifically prohibits penalizing employees for being homosexual or transgender (*Bostock v. Clayton County*, 2020, p. 1737). However, as constitutional law scholar and co-founder of BiLaw, an organization of bisexual and pansexual lawyers, Nancy Marcus (2020) highlights, "In failing to mention bisexuals, *Bostock* continues a harmful tradition of bisexual erasure in Supreme Court opinions" and does not explicitly protect bisexual employees (p. 231). This erasure of bisexual and pansexual experiences materially harms those who belong to these identities. Assistant Professor of Psychology Tangela Roberts notes:

Research on bisexuality has brought awareness to concerns of "Bisexuals experiencing more intimate partner violence, increased mental health concerns (depression, anxiety, etc), less screening for cervical cancers for AFAB (assigned female at birth) bisexual people, and Black bisexual people feeling less community support... All of these are symptoms of a larger problem, bisexual erasure. The

isolation that comes in feeling as if you are not visible to your communities, family, friends, and even the healthcare system at times needs to be met with visibility, inclusion, and affirmation" (Greenesmith, 2020, para. 15).

Although Assistant Professor Anthony Kreis declared, "what constitutes sex discrimination is now an open and shut case" (Moreau, 2020, para. 8) following *Bostock*, the majority opinion delivers a double whammy to bisexual and pansexual employees as the majority opinion microscopic and myopic focus on the statutory term of "sex" allows for employers to circumvent the *Bostock* ruling to discriminate against bisexual and pansexual employees.

As Professor of Law Danielle Weatherby and Assistant Professor of Law Ryan H. Nelson emphasize, an employer firing an individual for an attraction towards both men and women—regardless of the employee's sex—could avoid *Bostock* and Title VII protections (McGinley et al., 2020). An employer proving they terminated a bisexual employee while ignoring their sex would disconnect bisexuality from sex and Title VII's 'because of sex' protections, leaving bisexual employees vulnerable to employment discrimination. For example, lawyers representing evangelical church Bear Creek Bible Church and Braidwood Management, owned by anti-LGBTQ+ activist Steven Hotze, filed a brief in the middle of Bisexuality Awareness Week, arguing *Bostock's* Title VII protections do not apply to bisexual employees if "bi men are... discriminated against 'on equal terms as' bi women" (McGaughy, 2020, para. 2). The plaintiffs said:

Title VII prohibits sex discrimination only with respect to the sex of the affected employee or job applicant. There is nothing in Title VII that prohibits employers from discriminating because of the 'sex' of an employee or job applicant's sexual or romantic partners (McGaughy, 2020, para. 12).

On July 20, 2023, the United States Court of Appeals for the Fifth Circuit upheld exemptions for individual employers under the Religious Freedom Restoration Act from enforcement of Title VII's prohibition against discrimination of homosexual or transgender employees. The ruling vacated the circuit court's determination that discrimination against bisexual employees violates Title VII, while "declin[ing] to answer [this] open question" (*Braidwood Management v. EEOC*, 2023, p. 40) of Title VII's application to Bisexual employees.

These examples prove that absent an explicit protection of bisexual and nonbinary employees, which *Bostock* failed to do, these employees will continue to face employment discrimination. It also reveals that the courts do not intend to categorize "bisexual" and "nonbinary" under the categories of "gay" and "transgender" (which would establish broad employment protections under *Bostock*) because of their hesitancy to expand these protections in *Braidwood Management v. EEOC*.

It is incorrect to expect *Bostock* to address bisexuality based on the assumption that none of the three plaintiffs were bisexual themselves; a rebuttal begins to form. Critiquing *Bostock's* defense of protections for gay and transgender employees exposes how the majority opinion and its reliance on a narrow and myopic textualist reading of sex fails bisexuals. If that is the case, *Bostock* fails to live up to its reputation by activists and news sources alike as an overwhelmingly progressive decision for the LGBTQ+ community (Cohen, 2020).

Had the *Bostock* majority opinion addressed bisexual and pansexual employees working in the United States—who face employment discrimination just like gay, lesbian, and transgender employees—and included their experiences, *Bostock* could have closed the door for conservative attorneys and organizations to eviscerate the employment rights of over four million bisexual adults living in the United States (Sears et al., 2021). Instead, the door remains wide open for conservative litigants to potentially strike again.

The Gender Binary and Nonbinary Protections

Justice Gorsuch's textualist approach obscures the future of bisexual employment protections and leaves the fate of Title VII nonbinary protections unclear. As Associate Professor Jean Archibald clarifies, *Bostock* only explicitly prohibits discrimination based on whether an employee is "homosexual or transgender" (*Bostock v. Clayton County*, 2020, p. 1737) and does not explicitly ban discrimination based on all gender identities and sexual orientations (McGinley et al., 2020). Because nonbinary individuals do not identify with the sex they were assigned at birth, protections based on transgender status should, theoretically, protect nonbinary identities, as J.D. candidate from Cornell Law School A. Russel (2020) opines. The majority opinion does not explicitly define sex and gender; however, Justice Gorsuch relies on a gender binary to articulate employment discrimination, which implies that the court does not assume an expansive interpretation of gender that includes nonbinary individuals, exposing nonbinary employees to employment discrimination.

Justice Gorsuch invokes a gender binary when discussing hypothetical situations by exclusively discussing binary categories of man/woman and male/female when considering Title VII protections based on transgender status. For example, when discussing how transgender status passes the 'because of sex' test, the Court gives the example of:

[A]n employer fires a transgender person who was identified as a male at birth but who now identifies as a female. If the employer retains an otherwise identical employee who was identified as female at birth, the employer intentionally penalizes a person identified as male at birth for traits or actions that it tolerates in an employee identified as female at birth. (*Bostock v. Clayton County*, 2020, p. 1741)

Queer legal theory asks us to queer-y and question the implications of *Bostock's* use of the gender binary to filter its protections of LGBTQ+ individuals. *Bostock's* reliance on the problematic notion of a gender binary excludes and harms nonbinary people. By not providing examples of nonbinary employees and how *Bostock* would protect nonbinary identities, the Court likely did not have nonbinary transgender employees in mind when it prohibited Title VII discrimination based on transgender status and would be unlikely to determine nonbinary employees as being protected by transgender protections in future litigation. This gap in protection is not filled by Justice Gorsuch's textualist reading of 'because of sex' as employers could circumvent the question of an employee's sex at birth by simply discriminating against individuals whose gender identity is neither male nor female, thus bypassing a discussion of the employee's sex altogether. Allison Greenberg, J.D. candidate at the UC Irvine School of Law, concurs and specifies that *Bostock* abandons: "intersex individuals, asexual individuals, pansexual individuals, genderqueer individuals, Two-Spirit individuals, and the myriad other expressions of gender identity and sexual orientation that exist within human nature" (2022, p. 342).

With the majority opinion's silence on nonbinary identities, echoing the bisexual and pansexual erasure in the decision, and without explicitly detailing how the Court defines transgender—and whether it encompasses gender identities outside of a gender binary—*Bostock* leaves doors open for employers and lower courts to eviscerate nonbinary employment protections. Not only does the majority opinion abandon nonbinary employees from employment discrimination, but Alito's dissent also reinforces discriminatory notions of gender identity that endanger transgender and cisgender people alike.

Material Harms of a Gender Binary Shown Through Alito's Dissent

Justice Alito's dissent epitomized the consequences of relying on a gender binary. Justice Alito described a hypothetical situation that he claims the majority opinion would allow where a transgender person can identify as gender fluid and claim a right to enter a bathroom or locker room depending on the gender they identify with at that time (*Bostock v. Clayton County*, 2020, p. 1780). Justice Alito dangerously evoked the transgender predator restroom myth which claims that allowing transgender people access to bathrooms that align with their gender sanctions male sexual predators to inflict harm in women's bathrooms, perpetuated by conservative media and anti-LGBTQ+ proponents. However, a study conducted by the Williams Institute at the UCLA School of Law showed no evidence of this causal link and found that sexual predators commit crimes irrespective of current bathroom laws as sexual assault is already illegal (Hasenbush et al., 2019). However, the population most at risk are actually transgender youth, as a study published by the Harvard T.H. Chan School of Public Health (Murchison et al., 2019) found that more than one in four transgender and gender-nonbinary teens between the ages of 13-17 with restricted access to the locker rooms or bathrooms that best aligned with their gender identity had experiences with sexual assault. Not only does the transgender bathroom myth materially endanger transgender and nonbinary children, but cisgender people are harmed as well.

Aimee Toms, a 22-year-old Connecticut cisgender woman, was mistakenly identified as transgender in the women's restroom when she wore a baseball cap over her short hair that she cut to donate to cancer patients. Another woman said she was "disgusting" and did not "belong here" while she was washing her hands (Mcnamara, 2016, para. 4). Justice Alito's perpetuation of this harmful myth exposes cisgender women like Aimee Toms and transgender and nonbinary children to harassment and sexual violence. Justice Alito's reliance on a gender binary proves how binary assumptions of gender actively exclude nonbinary identities and perpetuate harm and bigotry against them, an example of Banovic's second framework of queer legal theory. Not only did the Court perpetuate power dynamics where transgender identities are met with transphobic violence from a predominantly cisgender society, but the Court also bolsters hierarchies where bisexual and nonbinary identities face prejudice within the LGBTQ+ community.

(Internal) Hierarchies Constructed

Queer legal theory asks us to interrogate how law not only constructs hierarchies privileging cisgender, heterosexual identities and experiences over others, but also how law can construct internal hierarchies within the LGBTQ+ community. In *Bostock,* bisexual and nonbinary identities are placed at the bottom of sexual orientation and gender identity hierarchies respectively, facing violence from both outside and inside the LGBTQ+ community.

Rather than face how bisexuality troubles the conception of a static sexual orientation binary of gay and straight, *Bostock* instead decides to place the 'rogue identity' of bisexuality within a hierarchy of LGBTQ+ identities. Through the exclusion of bisexual plaintiffs' experiences, the Supreme Court, as Nancy Marcus (2020) emphasizes,situates bisexuals below gays and lesbians within an internal hierarchy of LGBTQ+ identities. By only including the experiences of gay men and lesbian women in the majority opinion, *Bostock* privileges and validates these identities over bisexuality, perpetuating the bisexual erasure that Marcus (2020) underscores. Bisexual erasure becomes an endless cycle, as "the more courts do not

explicitly acknowledge the existence of bisexuals the less willing attorneys may be to bring discrimination cases on their behalf" (Marcus, 2020, p. 232), perpetually othering bisexuals and excluding them from protections in cases discussing LGBTQ+ rights. After *Bostock*, bisexual employees will likely face barriers that gay, lesbian, and binary transgender employees do not have to overcome.

Erasing bisexual experiences in *Bostock* not only conducts material harm by creating health disparities for bisexual people, but also psychology harms them. As Assistant Professor Heather Stewart (2021) details in her analysis of the epistemic consequences of bisexual erasure, bisexual erasure causes bisexual people to question the validity of their identity and experiences. Not only does it occur in the heterosexual Court and society at large, bisexual erasure additionally manifests within the LGBTQ+ community, resulting in what Jillian Todd Weiss (2003), who was previously a Professor of Law and Society at Ramapo College and Executive Director of the Transgender Legal Defense & Education Fund, coins as double discrimination. As a bisexual woman currently in a relationship with a man, Mrunmayi J. Salil described how her bisexuality was constantly invalidated when individuals within the LGBTQ+ community repeatedly asked her "why d[id]n't [she] just pick a side?" (Cakir, 2022, para. 6). Thomas York (2021), a bisexual man, described how when he began dating a man, members of his college's GSA (Gay-Straight Alliance) asked if he was coming out as gay now. Narratives of bisexual people experiencing bigotry within the LGBTQ+ community are all too common.

By only including examples of gay and lesbian employees, *Bostock* erases bisexuality as a valid sexual orientation. However, some legal scholars suggest that bisexual employees can claim Title VII protections as discrimination against bisexual employees typically occurs when they are in same-sex relationships (Marcus, 2020). Should *Bostock* force bisexuals to find employment protections by lumping themselves with homosexual workers, *Bostock* would cast a dark reminder of the stigma that bisexual people face of 'actually being gay,' invalidating their bisexual identity.

Because the *Bostock* Court similarly sterilizes nonbinary identities from discussion of transgender protections, an additional hierarchy materializes from the majority opinion: a gender hierarchy that places binary transgender identities above nonbinary ones. By only naming homosexual and transgender employees as receiving explicit Title VII protections, the court seems to interpret sex and gender as restrictive binaries (Parry 2022). When the gender binary is thoroughly used as a heuristic to map out transgender protections, it only follows that *Bostock* excludes nonbinary identities and places them below binary transgender identities. Just as Justice Gorsuch's textualist interpretation excludes bisexual as well as nonbinary identities, parallels can be drawn between the consequences of the hierarchies that place bisexuality and nonbinary identities at the bottom of sexual orientation and gender hierarchies respectively.

This legal privileging mirrors dynamics within the healthcare industry. Educational strategist at the University of British Columbia Frohard-Dourlent et al. (2016) argues that when binary transgender perspectives are at the center of medical discussions surrounding transgender identity, gender transitions are then assumed to only entail transitioning from one side of the gender binary to the other, smoothing over transgender identities and ignoring nonbinary experiences with nonlinear gender transitions. With this privileging comes barriers to gender-affirming care for nonbinary individuals (Kcomt, 2016).

Additionally, nonbinary people are harmed outside of the healthcare industry. A study authored by Dr. Cindy Veldhuis et al. (2018), an associate research scientist and research psychologist at the Columbia University School of Nursing,

found that roughly one in four nonbinary and gender-nonconforming individuals have experienced hate speech. *Bostock's* exclusive discussion of binary transgender employees perpetuates a binary-gendered environment where nonbinary individuals are exposed to increased microaggressions and bigotry when they cannot situate themselves within a binary context. This places them within a double bind, as they either must educate others on their nonbinary identity—which exposes them to increased bigotry and mental health exhaustion—or conform to a binary gender expression, erasing their identity (Flynn & Smith, 2021). Through the exclusion of nonbinary experiences within the majority opinion, *Bostock* excludes explicit protections for nonbinary employees and continues to normalize the gender binary which otherizes and creates a hostile context for nonbinary individuals.

Suggestions for an LGBTQ+ Inclusive Future

Through a heuristic of queer legal theory, this paper reveals *Bostock's* simplistic and myopic textualist reading of 'because of sex' and its reliance on an incorrect gender binary, failing to consider the complexities of sexual orientation and gender identity.

Instead, the majority opinion should have reaffirmed sex stereotyping and included the direct experiences of Ann Hopkins and the three plaintiffs in this court case. Had the Supreme Court centered sex stereotyping as the basis for the decision, the majority opinion would not have only reinforced protections for transgender employees, but sex stereotyping would also have protected bisexual employees, as the Equal Employment Opportunity Commission details in *Baldwin v. Foxx* (2015) the inextricable connection between sex stereotyping employment discrimination based on sexual orientation. Additionally, by focusing on the stories of the plaintiffs—and the eight million LGBTQ+ workers, and specifically, those who are not homosexual and binary transgender—the majority opinion may not have used textualism and instead used an interpretation that would have expanded protections for the entire LGBTQ+ community and unequivocally protected bisexual and nonbinary identities. Marcus (2020) gives a recommendation of what this inclusion of other identities outside of lesbian, gay, and transgender identities would look like, with specific emphasis on how *Bostock* should have included bisexual analysis within the decision. Marcus (2020) gives an example of what this analysis would like with an employer discriminating against a bisexual female employee in a relationship with a woman while not discriminating against a bisexual male employee who is also with a woman. In this example, 'sex' is the only difference while sexual orientation remains the same, showing how bisexual employees who face employment discrimination is rooted in sex discrimination. Bisexual inclusion rather than bisexual erasure would not only validate bisexual identities, but also strengthen LGBTQ+ rights and jurisprudence (Marcus, 2020).

Rather than rely on a strict gender binary and only include examples of binary transgender people, the Court should have foregone a textualist analysis and not implicitly assume gender as a binary and instead provide a thorough analysis that understands gender's inextricable relationship to sex (Severtson, 2021). In this situation, discrimination against nonbinary employees would indisputably violate Title VII as nonbinary identities would fall under the umbrella of transgender identities and be protected under Title VII's prohibition of discrimination based on transgender status. This would also extend Title VII's prohibition of employment discrimination 'because of sex' to prohibit discrimination 'because of gender,' without amending the ruling. However, following this ruling, Congress should still amend Title VII to explicitly prohibit discrimination.

The LGBTQ+ community and activists should pay heed to Justice

Kavanaugh's and Justice Alito's dissents that it is Congress's role to expand the rights of LGBTQ+ individuals. As of July 11, 2023, only "17 % of LGBTQ population lives in states explicitly interpreting existing prohibition on sex discrimination to include sexual orientation and/or gender identity" (Movement Advancement Project, 2023, para. 7). Congress should pass legislation like the Equality Act (2021) to amend all federal antidiscrimination laws, including Title VII, to prohibit discrimination—not only related to employment but public accommodations—based on sexual orientation and gender identity. While federal legislation continues to stall within both houses of Congress, possible inroads to expand LGBTQ+ through the legal system still remain.

Justice Alito argues in his dissent that the *Bostock* opinion will have a widespread effect, as he lists the over 150 federal statutes that currently prohibit discrimination based on sex will be impacted by the ruling (*Bostock v. Clayton County*, 2020, p. 1776). Thanks to Justice Alito, Civil rights attorneys now have a clear roadmap of the 150 federal statutes they can mount challenges to and expand protections for LGBTQ+ people in a plethora of areas including education and health care (Quinn, 2023). These attornies may be able to exploit Justice Alito's interpretation of textualism to mount challenges and expand rights to theh LGBTQ+ community.

As civil rights lawyers proceed to exploit Justice Alito's pointing them "right to buried treasure" (Kalmbacher, 2020, para. 15), the EEOC has taken steps to support nonbinary and bisexual employees. They have introduced the nonbinary 'X' gender marker as an option for filing discrimination charges (U.S. Equal Employment Opportunity Commission, 2022). Additionally, the EEOC remains committed to its determination that employment discrimination based on sexual orientation violates Title VII (*Baldwin v. Foxx*, 2015). However, it is anticipated that these protections will face legal challenges in court.

Conclusion

Queer legal theory exposes *Bostock's* cursory assumptions of gender and transgender identities and connects how these legal questions have political and material consequences. By not explicitly defining gender or stating whether transgender encompasses nonbinary identities and leaving these rights, as well as bisexual protections, in limbo, *Bostock* leaves a negative space for conservative litigators to exploit. Just as how the Bear Creek Bible Church and Braidwood Management tested bisexual protections, it is only a matter of time before nonbinary protections are placed under the same scrutiny. With waves of anti-LGBTQ+ legislation and policies coming forth, nonbinary protections are in a precarious position, without explicit Title VII protections to shield them. Through *Bosto*ck, queer legal theory proves how identities that fall out of binary categories, including nonbinary and bisexual people, face violence when the law fails to conform to these identities. Due to the law's static and rigid nature, as evidenced by the thorough legal history of bisexual erasure within the courts (Marcus, 2020) and the resistance to including bisexual and nonbinary experiences within LGBTQ+ decisions, queer legal theory asks us to reconsider whether decisions made by the Supreme Court can continue to be an avenue to expand LGBTQ+ rights if the judiciary continues to grasp onto and enforce binary conceptions of gender identity and sexual orientation.

Although doctors no longer slap the bottoms of babies and declare, 'it's a girl/boy!' we still come into the world assigned a gender within the rigid gender binary that is firmly entrenched within the inflexible confines of societal norms. Therefore, it is no surprise that the highest court in the land continues to implicitly reinforce binaries of gender and sexuality. However, queer legal theory challenges these

assumptions, acknowledges the diversity of gender expressions and sexual orientations, and gives us the tools to "dislodg[e]… hierarchies" (Banović, 2022, p. 16), granting us the possibility to move towards a social and legal understanding that validates and envisions a future for Brie Boyle and all LGBTQ+ people.

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Shout Through the Air: Rhetoric of China's Lower-Class "Toilet Girl" as Empowerment and Subversion

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Abstract

Cemei "Toilet Girls," an internet subculture that utilizes transgressive, "diarrhea-style" rhetorical practices to denigrate a range of social norms upon young women, has become the center of disputes on the Chinese internet in recent years. This paper examines the activist potential of Toilet Girls based on the community's decentralized, grassroot structure, intersectional agenda, and unusual rhetoric. A literature review of key texts on Chinese women's rights issues, like Pun Ngai's *Women Factory Workers in Global Workplace*, places toilet girl's rhetoric within gender and socioeconomic inequalities stemming from China's economic reform in 1978.

After highlighting the lack of scholarly literature on the Cemei, this paper performs a qualitative analysis of Toilet Girl Weibo forums. It is demonstrated that, toilet girl's "diarrhea-style rhetoric" serves to, despite the government censorship, reconstruct social and cultural narratives on young women, reverse the established dominating value systems, and breaks cultural taboos against patriarchal and classist oppression. To conclude, the uniqueness and potential of the Toilet Girls, placed in the context of feminism and class struggle in China, as well as their ability to carve out new forms of digital subversions for future activism in general, is undeniable.

1. Introduction

"I just want to exclaim that being a poor woman is so hard" (很想感叹一下琼女人真的好难). This is an excerpt from post No. A1007, published by a Weibo (microblogging) account on the Chinese internet called Reincarnated As A Poor Bot (转生之我是穷人bot). It also encapsulates the dominant motif among the user comments on this account. Most are slice-of-life stories and complaints from teenage girls suffering from poverty, misogynistic social and familial expectations, and mental illness in China. In this setting, netizens playfully address themselves as

"toilet girls" (厕妹) and the social media accounts they use as "internet toilet" (网络公厕). The "toilet" in "toilet girls" and "internet toilet" comes from slang for anonymous accounts on China's Twitter-like site Weibo, which are spaces where users feel free to vent, to put it crudely, diarrhea-style; it has since come to refer to similarly freewheeling affinity groups and their members, though the exact origins of the "toilet girl" moniker are still debated (Chen). More precisely, the audience girls of Reincarnated As A Poor Bot belongs to a main subgroup of the "toilet girl" community as they gather below accounts of "poverty toilet," which have their contents distinct from other "internet toilets" for the focused discussions on the experiences in lower-class communities.

In such online spaces, these toilet girls talk about unpaid internships that left them with thick callouses on their hands; they complain about their alcoholic fathers, possessive mothers, and spoiled siblings. They also share their experiences of routinely bargaining for a bowl of millet gruel in the school cafeteria or a group pack of cheap menstrual pads on wholesale platforms. But who are these toilet girls in the "poverty toilet," situated in their wider historical and social contexts? What drives them, and what changes are they knowingly or unknowingly bringing about?

The stories of impoverished young women unfold against the complicated background of gender and class politics in China; on the one hand, the economic inequities in China have been widening since the economic reforms and opening to foreign investment in 1978, when China was just beginning its transition to a market-based economy. However, in recent years, class discourse has been disappearing; when it does appear, it is largely depoliticized to focus more on theoretical social stratification in official and mainstream narratives "with the formation of a new working class structure" (Ngai 53). In this sense, the sentimental rhetoric of toilet girls directly confronts the issue of wealth inequality, often with anger and dark humor. In this sense, it suggests a return (of a kind) of class discourse. Moreover, although the digital advocacy of women's rights is nothing new, with 2020 dubbed by many as "the first year of China's feminist awakening," feminism-adjacent discussions are usually dominated by liberal feminists concerned with the cultural constraints encountered by women in general, such as body anxiety and freedom of dress without much deliberate stress on the most vulnerable groups of Chinese women.

In other words, socioeconomic inequities by and large have not been successfully integrated into mainstream feminist activism, leading to considerable blindspots. In turn, toilet girl rhetoric stresses the intersection of diffused networks of power, from gender to class to region, with a focus on the experiences and travails of impoverished women. Many first came to hear the term "toilet girl" following a shocking piece of news on cyberbullying. A young girl in Hong Kong, Yinai, was viciously bullied by a group of toilet girls for months, ultimately jumping from a building to end her life (Chen). Thereafter, "toilet girl" seems to become a synonym for spiteful young women, while the socioeconomic and gender dynamics of their communities are swept out of view. This is all the more reason to re-examine toilet-girl culture through a careful rhetorical and sociological lens.

Thanks to the rise of online culture, toilet girls could freely express their discontent towards socioeconomic gaps and gender norms in contemporary China, forming their own subculture defined by criticism of class stratification and gender politics in China; therefore, toilte girls' rhetoric displays the potential to transcend mainstream feminist, class, and respectability politics by encouraging the wider movement to adopt a more intersectional agenda that accounts for the complex interplay of a wide variety of social and cultural practices and institutions.

In this paper, I aim to examine this activist potential from a rhetorical angle.

First, I review the historical, theoretical, and rhetorical literature in relation to lower-class feminist struggles of the past, showing a notable lack of contemporary, serious research on the rhetoric of toilet girls in particular. I then turn to investigate the rhetorical strategies that toilet girls adopt to express their discontent, particularly at the genesis of their social movement, including changing societal perceptions, creating sites of collective identification, and challenging symbolic norms; the limitations of enforcing exclusion and excessive obscenity, practices which distinguish toilet girls from more conventional social activists, are also discussed.

2. Literature Review

In her article "Chinese Social Stratification and Social Mobility," Yanjie Bian provides an overview of China's post-Reform and Opening (1978-present) widening socio-economic gaps and reduced opportunities for social mobility for lower-class citizens. While Bian, for her part, appreciates the newfound opportunities for vocational mobility in this newly marketized China, Ravni Thankur, by contrast, stresses the pronounced class inequality of this period, especially stratification between technical, private-sector, and state-sector workers. Xin Liu's account takes up a more empirical analysis of these issues based on sociologist Max Weber's concept of domination and Kornai's coordination theory, with an eye to the unequal distribution of income under this semi-liberalized scheme. Other academics have noted how the Chinese Communist Party's (CCP) official narratives have gradually decentered or at least depoliticized class struggle, focusing more on stratification theories (Ngai).

Simultaneously, the rise of identity politics in post-socialist China has been linked to these developments, with much attention given to the prominent Chinese feminist activists (Wang). Moreover, China is a country permeated by Confucian conventions, which contain patriarchal ideologies and behavioral codes, a kind of quasi-caste system which places women below men in marriage and family life. Though the Communist government initially placed great emphasis on gender equality during the socialist reforms of the 1950s, this long-standing patriarchal culture has not been eradicated in the Chinese society (Gao 114). In the post-Reform era, as the gender equality is no longer promised as an essential component of China's governmental tenets, Chinese women's political demands are further deprioritized. Yet even under these bleak circumstances (or perhaps because of them), feminism has increasingly taken center stage in citizen-driven social debates in recent decades (Hou 79), despite these being highly censored and often concealed by algorithmic manipulation. Usually, it is white-collar, urban women more sympathetic to the discursive and ideological aims of modern capitalism (wealth and individual freedoms) who are permitted visibility. These accounts present the development and bottlenecking of feminism on the Chinese internet, specifically the ways in which some Chinese women have adopted discourses intended to challenge patriarchal norms and safeguard gender equality by using social media platforms to criticize conservative values and question the ongoing stigmatization of feminist activists by mainstream media.

Taken together, however, these accounts reveal a significant blind spot when it comes to the plight of lower-class women in China today. While Pun Ngai's *Made in China: Women Factory Workers in a Global Workplace* offers a fascinating portrait of Chinese women working in the manufacturing sector in various southeastern special economic zones in the 1990s, highlighting many of the

competing demands imposed upon them by patriarchy, state authorities, and global capitalism, it simply cannot offer a timely, precise analysis of twenty-first century lower-class women in China given how the country's socioeconomic dynamics have changed drastically in the intervening years. Thus, digital spaces offer key, real-time insights into the evolving experiences and accounts of new generations of young, lower-class women.

Besides driving us to study China's lower-class women in particular, the gap also suggests turning to comparative or analogical reviews of historical literature on social movements with similar intersectional emphases on class, gender, age, etc. For example, *Riot Grrrl: Revolutions* by Jessica Rosenberg and Gitana Garofalo concentrates on another teenage-girl-based social movement with a deliberate focus on the reclamation of femininity in youth culture, with the revolutionary addition of "growls" as provocative challenges to patriarchal attempts to tame teenage girls (Rosenberg and Garofalo).

Similarly, research on internet-based feminist movements like Hester Baer's "Redoing Feminism: Digital Activism, Body Politics, and Neoliberalism" discusses classic cases of transregional articulations in feminist movements, including #MeToo and other hashtag-based Twitter campaigns, concluding that online campaigns nowadays, though restricted by neoliberal parameters, provide feminist activists with opportunities for naming and conjuring novel social formations (Baer 25). Several studies also investigate how other teenage girls engage in class and gender discourse: Jessica Francombe-Webb and Michael Silk discuss the inculcation of gender-normative temperaments in upper-middle-class girls aged thirteen to fifteen, drawing attention to how class divisions enable the normalized disciplining of these individuals under the guise of social propriety (Francombe-Webb and Silk 652). *Girlhood and the Politics of Place*, edited by Claudia Mitchell and Carrie Rentschler, offers insight into how territorialized labels play into activists' collective creation of "stages" and practices of promoting social change. Still, even here in this collection of intersectional research on girlhood and feminist activism, we witness again and again the centering of upper-middle-class girls and the sidelining of more radical attempts to engage with lower-class or working-class young women and their social and discursive worlds (Mitchell and Rentschler).

Before turning to investigate the toilet girl phenomenon in greater depth, we must first turn to some key terms. Concepts of class are often borrowed from Karl Marx's analysis of class relations and inter-class struggles under capitalism (Marx and Engels). In this framework, class names a position chiefly between owners of productive resources (capitalists/the bourgeoisie) and those who sell their labor power to them (workers/producers/proletarians), with the surplus value generated by the latter group seized by the former in the form of profits and proportionate social power. A modified, more diffused form of this notion of class is offered by Bourdieu that, while informed by Marx, also emphasized key cultural and symbolic differentials within Marx's class system such as prestige, educational attainment, and social network (Bourdieu). With regard to gendered power dynamics, Sylvia Walby defines patriarchy as "a system of social structures and practices in which men dominate, oppress, and exploit women (Walby 213)." Hooks further elaborates on this concept by emphasizing its structural, ideological feature: compared to earlier terms like "male chauvinism" and "sexism," appealing to "patriarchy" identifies a system of norms and hierarchies where both men and women may be enlisted in the service of gender-based oppression, which thus better explains the well-reported role of female oppressors in toilet girls' lives (Hooks).

These frameworks give us some insight into the dilemmas facing predominantly lower-class toilet girls, who are educated and disciplined as members

of the reserve labor force to be exploited in the workplace; they are thus squeezed from two sides since they bear socioeconomic pressure from their domestic environments, in which the patriarchal family must struggle to survive excessive work and low wages while maintaining its own internal logic, as well as ideological indoctrination from schooling which celebrates an unmistakably capitalist work ethic (cf. Althusser 1970). This contradictory imperative (accepting and navigating both the male-dominated, hierarchal home and the difference-effacing, dehumanizing market) informs the values and struggles of average lower-class students—in this case, so-called toilet girls.

To decipher the toilet girls' accounts, we must consider rhetoric; in particular, narrative is the key to understand how their stories are told. In *Seriality and Storytelling in Social Media* by Ruth Page, the author theorizes the textual continuity underlying highly fragmented social media posts (Page 31). *Content Crowdfunding and Emotional Resonance: An Analysis on the Rise of Artificial Bots on Weibo* by Ruoyin Chen offers an analysis of the form and contextual origins of depersonalized bot accounts, which has become a popular mean of information distribution on the Chinese internet (and are thus used by toilet girls as their major means of communicating with each other) (Chen). Several studies also look at narrative as it relates to identity. For example, Margaret R. Somers contends that narrative provides the conceptual impetus for social actors to incorporate and assume particular identities and roles (Somers 605). Another way for toilet girls to solidify their collective identity is polarization: as a rhetorical phenomenon in which the societal public is "coalesced into two or more highly contrasting, mutually exclusive groups," polarizing strategies have already been widely employed in social and political mobilizations in the past, such as Nixon's presidential campaign in the 1960s (King and Anderson 1971).

Going beyond rhetorical strategies commonly adopted by social movements, such as altering perception and identification, toilet girls are notable for their willingness to subvert rhetorical and social taboos. *In Obscenity and Protest*, Haig A. Bosmajian introduces verbal obscenity as a nontraditional strategy to mask, or simply to substitute, insecurity and hesitation on the part of protestors by means of "symbolic aggression" (Bosmajian 9). J. Dan Rothwell argues instead that the principal purpose of such rhetorical strategies is capturing public attention, disrupting social norms, and solidifying group identity (Rothwell). For rhetorical strategies of satire and reappropriation, Kathryn Olson and Clark D. Olson (2004) provide a comprehensive overview of the pure persuasive function and symbolic subversion brought about by satirical rhetoric, which is in line with Brontsema's look at playful, satirical reappropriation; after investigating the use of irony in general, this study places the theorized concepts into concrete historical contexts and events surrounding the reclaiming of the disparaging word "queer" to demonstrate the evolution and features of reappropriation, which is a key feature of the toilet girl phenomenon as well (Brontsema). Lastly, rhetorical literature studying culture jamming practices relates to the rhetoric of toilet girls in various ways. In "Pranking Rhetoric: 'Culture Jamming' as Media Activism," the authors introduce pranking as a radical form of activism containing not only satirical but also auto-deconstructive features, while *Culture Jamming: Activism and the Art of Cultural Resistance*, edited by Marilyn DeLaure and Moritz Fink, further conceptualizes the range of this phenomenon's rhetorical and symbolic features through the lens of past culture-jam campaigns, providing a solid foundation for the comparative study of toilet girls' attempts to subvert the "empire of signs" wedding patriarchal and class systems.

In sum, gaps in existing historical, theoretical, and rhetorical literature make careful analysis of toilet girls' political and economic surroundings, rhetoric,

and social existence urgent and necessary. Such an account would give us a clearer picture of contemporary social cleavages and change, digital communities, and intersectional feminism in China, with potential insights for individuals and activists across vastly different contexts.

3. Analysis

Systems of class stratification and patriarchy in China have become increasingly enmeshed since the 1978 economic reforms (Ngai). Squeezed by the intersecting pressures at the bottoms of these systems, toilet girls find social media as the outlet of last resort for their pent-up grievances. The rhetorical strategies employed illustrate powerful connections to many of the strategies adopted by other social movements at their genesis. Whether this will ultimately empower lower-class women in China to take "real-world" stands against "socialism with Chinese characteristics" (more accurately, state capitalism and bureaucratic collectivism) and neo-Confucian patriarchal norms remains to be seen, but it is a promising—if admittedly somewhat bumpy—start.

Against the background of China's media environment and censorship regime, which endeavor to downplay subaltern voices that might foment social unrest, this paper will focus on how toilet girls transgress social taboos, unveil the "sad reality" they inhabit using fragmentary, marginalized perspectives, establish their collective identity via we-they divisions and imitative intimacy, and pose symbolic challenges to social norms through deviant language. Ultimately, these strategies appear as double-edged swords, with both promises and pitfalls for toilet girls' would-be social movement.

3.1. Narrative: Transforming Social Perception

The narratives or storytelling tactics of toilet girls are their primary means of communicating their lived experiences and changing netizens' perception of social realities, which is a key stage in the development of any social movement.

Before moving on to textual analysis of these narratives, I investigate the media infrastructure underpinning toilet girl rhetoric. These netizens use a specific type of account known as "bots" on China's Twitter-like social-media platform Weibo. These bots are accounts, and counterintuitively, are actually operated by humans, yet they are masked as nonhuman agents who dutifully post the usually vetted private submissions of users, helping mask toilet girls' identities (Yuleyingtang).

Having cast off the shackles of personal identity, the toilet girls are free to vent their discontent toward their families and schools, in contrast to the "uplifting" narratives prioritized since 2013 (CMP Staff). For this reason, toilet girls call their bot posts "spewing black mud" (吐黑泥), often beginning their narrations with "Let me spew some black mud" (让我来吐点黑泥), which playfully suggests that their narratives, juxtaposed against more conventional, mainstream narratives, are essentially gloomy, filthy, excremental, and thus unacceptable.

Moving on to toilet girls' intended audience, we find two main categories. Messages (or "shouts into the air," in toilet girls' language) either accuse the girls' parents, friends, and schools of being oppressive forces in their lives, or else seek help from their fellow toilet girls. The former and the latter could be distinguished easily through different initial references addressing different target audiences; the latter type of posts is generally much shorter in length, emphasizing emotional

expressions and pragmatic resorts over experiences themselves. Other styles of messages, such as self-narrations (which contain complaints or stories about an individual's struggles), range from several sentences to hundreds of words and are notable for their explicit lack of a specific target audience. Nonetheless, as a general feature of texts on social media platforms (Sadler), most messages are highly fragmented and abbreviated; therefore, the scope of effective, coherent counter-narratives is limited, and literary elaborations are mostly omitted. Even the lengthiest self-narrations, while containing broader contextualization on family background, hone in on a singular event reflective of the toilet girl's struggles under poverty, gender inequality, and sometimes mental illness. (see Appendix A)

> B780 Contribution: So sad. Today in the dormitory, some roommates were talking about menstrual pads. They mockingly asked, "How could someone have never used menstrual pads before?" in a laughing voice followed by some indecent jokes. I was paralyzed in the moment. When I was a child, no one took care of me, and I often couldn't use them. I even thought that I had a physical ailment that made me bleed. I didn't even have money to buy a paper pad. I won't blame them for not having had this experience, but I still feel that my wounds were torn open. Painful and hard to hear…
>
> (B780【投稿】好难过，今天在寝室室友说起卫生巾的事情，他们在感叹怎么可能有人没有用过卫生巾，还发出了嘲笑的声音甚至开起了一些不雅的玩笑，我当时表情都僵住了，可是我小时候没人管的时候时常是用不上的，所以老觉得自己生理上有疾病，也没有钱买拿纸垫过，他们没有这种经历确实不怪他们，可是我还是觉得自己以前的伤口又被撕裂开，好痛好难受。)

The sample text above is a post excerpt (contribution No. B780) from Reincarnated As A Poor Bot, in which an anonymous toilet girl narrates a moment of being mocked and attacked for her poverty and ignorance of menstrual pads. While the tale is short and simple, it pushes stigmatized issues and struggles into public view. Moreover, as these fragments accumulate on the "bot" account, they begin to form a stream of marginalized experiences, manifesting the sheer numbers and potential collective power of oppressed women and girls, who now symbolically occupy the digital public square which previously excluded lower-class young women.

Such moments of confluence are shown in the toilet girls' "shouts in the air" to other girls. In these posts, like the sample text discussing switching jobs, they share their experiences with workplace struggles and domestic abuse based on their shared identity as lower-class young women living in contemporary China, asking each other for life advice. These stories not only serve a pragmatic function for toilet girls, but also cement and establish their narrative presence and thus, by extension, their communal coherence.

According to Margaret Somers, narrative determines the way in which people understand and interpret the world (Somers). For toilet girls, narratives are both hyper-intimate and broadly decontextualized. When these fragmented messages are aggregated and published through bot intermediaries, a coherent group identity takes shape. In turn, when these fragmented narratives derived from toilet girls' daily lives come to light, the broader public is made more keenly aware of the existence of patriarchal and class oppressions in the day-to-day life of many.

Yet when considering toilet girls' narratives as the rhetorical genesis of a

social movement, one thing to note is the limited publicity and media exposure permitted by these bot-like accounts. While they provide privacy and in-group cohesion, this well-defined cultural sphere also prevents outsiders from entering their shared space, limiting members of the wider public's ability to encounter tales which may change their perception of social realities, not to mention further coalition building and recognition.

3.2. Naming: Forming and Transforming Self-Identification

In evaluating the genesis of the toilet-girls phenomenon, another key facet to analyze is the formation and development of their identity through both collective identification and polarizing rhetoric against their perceived oppressors. The "oppressors" category is wide-ranging and diffused, yet rhetorically there are two representative types: domestic patriarchy and economic inequality. Unique in the toilet girl rhetoric is its implication of both direct oppressors, ones privileged in terms of socioeconomic class and gender in real life, as well as the strangers on the internet who try to understand "toilet culture" from a well-meaning but ultimately condescending, classist view. The toilet girls thereby construct a highly systematic, intersectional, and coherent rhetorical environment where even passive bystanders are implicated in the perpetuation of class-based and patriarchal oppression.

Table 1. *Uses of Naming Against Oppressors in Toilet Girl's Rhetoric*

Type of Oppressor	Slang	Meaning
Real-world privileged types	豹豹猫猫 The Leopard and Cat	Father and Mother
	富人 The rich	Wealthy, powerful people
	白富美 Fair, rich, beautiful	Young, conventionally attractive female friends with socially decent or better family backgrounds
	湿疣Condyloma	(Usually annoying) roommate
	迪迪 Didi	Little brothers
	健全人 Health nuts	People who explicitly exclude or reproach toilet girls for mental instability or illness
Outsider	萌萌人/萌萌/mmr Newbs	Judgmental newcomers who don't understand "toilet culture"

The first type of oppressor most often includes roommates (particularly wealthy ones), friends, parents, and siblings (mostly younger brothers), who are deemed to exercise unjustified power over the girls' lives. Socioeconomic labels are blunt ("the rich"). Notably, toilet girls commonly address their wealthy female friends as "white, rich, and beautiful," an outdated Chinese buzzword to describe a young, attractive woman with a socially acceptable family background. Indeed, the very use of outdated buzzword is itself a rhetorical feature shared by many subcultural groups to differentiate themselves from the mainstream.

Such rhetorical preferences demonstrates that rather than struggling to eliminate or avoid labels of lower-class identity, toilet girls playfully accept and reclaim their socioeconomically inferior position of speech, willingly positioning themselves in opposition to "the rich." Similarly, toilet girls address people who explicitly exclude or reproach them for mental instability as "health nuts." This

illustrates how toilet girls adopt labels of being "mentally inadequate" and "emotional," reappropriating them as signs of power.

Toilet girl rhetoric, as this suggests, is often interpersonal rather than systemic in nature, in that that they appeal more to target subjects in their immediate, real-life surroundings rather than an abstract group of oppressors "out there." Yet their resignation and frustration invariably speak to structural, systemic presence of oppression and exclusion. In many of the toilet girls' posts, they begin with a precisely worded accusation, but end their posts reach a despairing wail addressed at this impossibly large Oppressor: "Go to hell, all of you!" (你们都去死).

The latter type of oppressor includes other casual netizens—mostly those that passively follow the mainstream culture. They may occasionally encounter or even deliberately attempt to enter the cultural territory of toilet girl, strenuously trying to understand their communication and who often preach conformity to them. Toilet girls address these people as what I have rendered "newbs" (in Chinese, this word means "cuties," and as a reduplicated word, it sounds childish). By referring to outsiders as adorable, childlike beings, the toilet girl counters the classist attitudes of the casual passers-by with studied mirroring.

While toilet girls are often critiqued for being immature and childish, by using such labels, they attempt to playfully flip this script, highlighting that these intruders are in fact the ones who are too ignorant and immature to recognize socioeconomic problems embedded in modern Chinese life. Moreover, "cuties" demonstrates the girls' challenge to mainstream values. These external voices often criticize toilet girls for being "mean" and even "malicious," appealing to mainstream values like "kindness" and "generosity." Addressing these individuals as cute not only reverses those power dynamics, but also displays a sense of mockery towards mainstream narratives, values, and aspirations.

Ultimately, "us/them" divisions are made against two central antagonists: the direct oppressors and casual observers. Inherent in this dichotomy is an expression of rebellion against the class inequalities and the patriarchal, domestic microaggressions, a promising foundation for establishing a coherent communal identity.

Next, I analyze toilet girls' preferred way of addressing themselves. When discussing themselves or members of their own community, toilet girls reappropriate disparaging words to serve as identifying markers. Primarily, "toilet girl" was a stigmatizing attempt that netizens put forward to address the girls in the online community with contempt and despise upon the girls' diarrhea-style language that transgressed linguistic formalities. Labeling theory might suggest that the name pins the toilet girls' self-perceptions on the position of deviance (DeFleur and Goffman 127), yet they also showcase an initiative to playfully transform and adopt this insult. According to Brontsema, reappropriation of a disparaging word is usually aimed at value reversal, neutralization, or the exploitation of stigma. In this sense, the girls' rhetorical self-identification as "toilet girl" helps mark their statuses as the marginalized and exiled, disrupting and thus dismantling courtesies and virtues under mainstream acknowledgement.

Another most well-known and effective practice is calling themselves "the poor," as demonstrated by Reincarnated As A Poor Bot. Such use of "the poor" serves as a direct implication of classist power structures in modern China, and a reminder of toilet girls' anguish and discontent within that structure. For toilet girls, explicitly identifying themselves "the poor" further reverses the established value systems that degrades lower-class people, as well as using it to galvanize these wretched of the earth.

The appropriation inherent in the methodology for how toilet girls address

each other also contributes to the unity of their cultural identity. Toilet girls ironically call each other "baby" or "husband" when commenting under each other's posts sent by the bots. This reappropriation serves as a playful sendup of rigid, traditional family roles and responsibilities. Indeed, there are analogues and similarities found in Black, queer ball culture, where "houses" serve as alternative families to shelter gender and sexual minorities ostracized by societal support systems (Bailey 365). To some extent, labeling each other as family members may also imply that toilet girls register affection and intimate support within their internet subcultural circle, imitating and reinterpreting the social structures outside their community but ultimately reappropriating them to denude the original labels of their exclusionary bite.

In sum, toilet girls effectively establish their unique identities as an emerging social group through what I call resistance mindedness. They surgically target enemies (and even friends) with playful, reappropriated terms, creating a sense of shared language, grievance, and belonging.

3.3. Language Deviance: Challenging Symbolic Norms

The most subversive yet controversial feature of the toilet girls' rhetoric is how they disturb language itself as part of their symbolic challenge to social norms. Essentially, it is hard for those adorable newbies to decipher the rhetoric of toilet girls, because the language of the posts goes against normal linguistic practices and resists casual interpretation by out-group members.

> 【TG】 Accidentally heard a classmate saying that her leopard cat asked her to run to Liben, and that she talked to them for a long time until they agreed to allow her to stay. Mental breakdown. Everyone in my class is a minus child despite me. I borrowed ten thousand from my family and could not borrow any more to join this class. I could eat for a couple of days with the money you guys spend when skipping school to get your hair done.
>
> (【TG】偶然听见补课班的同桌说她豹猫本来要叫她润去立本的 劝了豹猫好久才让她留下来 好崩溃 本人在的这个补课班都是负人小 孩 我是家里借到不能再借才凑了1w来的 你们旷课出去做一次头发的 钱够我吃好几天饭阿.)

This is a post from the bot account Who Stole My Rich Life (谁偷走了我的富 人生活). There are puzzling words like "Liben" (立本), "leopard cat," and "minus people" (负人), which are all homophones in Chinese: "Liben" refers to Japan, "leopard cat" refers to parents, and "minus people" to the rich.

The use of homophones is a longstanding feature on the Chinese internet, thanks to its ability to avoid strict censorship, as well as the inherently homophonic nature of Chinese due to its limited phonetic inventory. Yet the toilet girls' excessive use of such substitution means something more. Toilet girls deliberately practice excessive homophones in their posts to prevent outsiders from comprehending their conversations and invading their cultural space. In addition, the extreme use of homophones woven into the text creates the effect of symbolic overflow and presents itself almost as a parody to the truly necessary use of homophones under censorship— a sorrowful mockery of the rhetorical constraints on the Chinese internet. This highly homophonic in-group language serves as a double-edged sword, providing strong cohesion within their subculture group, but also limiting their community expansion.

Another rhetorical feature, disturbing the language norms and posing symbolic challenges, is the chaotic syntax. In general, these diarrhea-style posts either lack any punctuation or are split into tiny pieces by immediate repetition of punctuation marks. The post marked as 6421 (see Appendix B) illustrates the former feature, which automatically speeds up the reading and creates a tone of a venting, jabbering rush, especially for long paragraphs. By contrast, repetition of punctuation marks slows down the reading and indicates a hesitant, stuttering tone. This often conveys a sense of disappointment and resignation. Yet both syntactical features deviate from the norm, implying the abnormal tones and emotional distress of the writer. Thus, we can see how the syntactical choices employed by toilet girls also provide outlets to express the ordinarily unexpressed in a subversive manner.

Finally, toilet girls employ copious obscenity in their rhetoric as well. They randomly drop curses like "go to hell" (去死) or "go get killed in a car crash" (创死) in any conversation, demonstrating their firsthand, seething hatred of oppressive social rules and inequalities, breaking with the taboo against invoking death or harm; notably, common swear words related to women bodies, sexualities, and maternity rarely appear in toilet girls' rhetoric, which reasonably corresponds with their radical disengagement from mainstream and an emerging awareness to reject the underlying misogyny in general linguistic practices.

This obscene, transgressive rhetorical practice appears somewhat unscrupulous in light of Yinai's suicide, mentioned in this paper's introduction, as it was the toilet girls' cruel jokes and curses which caused Yinai to jump from the building. Their aggressive language also contributes to factional infighting, rivalries, and cyberbullying. As a result, toilet girls and their rhetoric have not been widely accepted or acknowledged by Marxists, liberal feminists, and radical feminists. This suggests additional constraints on their community growth and coalition building. It is this tension embedded in the toilet girls' rhetoric which will shape the future development and evolution of the community.

Ultimately, we might ask, do trade-offs have to be made between the symbolic subversiveness and social acceptance of the toilet girls? Since their campaigns lack a centralized, organized structure, to say nothing of a unifying political agenda, toilet girls may be said to resemble newer, less conventional social movements like culture jamming, where a similar expressiveness, playful resistance, and constant state of instability are actually virtues that sustain more essential subversions of power.

4. Conclusion

The emergence and development of toilet girl communities and rhetorical styles are opening up a new space of discourse between class and gender politics in China. By adopting fragmented narratives communicated via bot accounts on Weibo, toilet girls offer each other, and the wider public, close-up looks at how lower-class girls are being exploited, oppressed, and looked down upon in their daily lives. This holds out the possibility of transforming at least some people's consciousness of social injustice. Moreover, by using strategies of polarization and reappropriation, toilet girls further position themselves against the oppressors and reaffirm their collective identification. Similarly, the playful employment of homophones, atypical syntax, and obscenity illustrate their transgression against symbolic norms.

Though the toilet girls' rhetorical reach is limited by their intentionally insular slang and (to others) off-putting behaviors, it is undeniable that this group is uniquely positioned to inject some of the subversive power of intersectional resistance to class, gender, geographic, and other forms of oppression into wider digital and real-

world communities. With China's post-COVID economic recovery looking sluggish, this is an opportune moment for these keyboard warriors to expose issues too often concealed, as more and more individuals feel some degree of economic hurt. Under a context where activists and dissidents lack appropriate means to channel their demands, toilet girls' rhetoric, which features a playful deviance (echoing the growing popularity of so-called "hysterical literature" (发疯文学) on the Chinese internet), might inspire digital pranking strategies in general to evolve as a form of organized resistance.

This paper is intended to spotlight the emerging voices of lower-class women in China. Until now, this phenomenon largely has been overlooked by academics despite its profound relevance for scholars, activists, and observers alike. Future research would benefit from including the firsthand accounts of toilet girls—if nothing else, to give these young women a platform and avoid excessive speculation around intention. Additionally, it is important to get a fuller demographic picture of toilet girls, examine other intragroup obstacles to solidarity (such as prevalent ableism), and bring other methodological and disciplinary frameworks to bear on understanding this unique, subversive subculture.

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Appendix A

Categories of toilet-girl posts with sample texts

Type	Audience	Example
"Shouts into the air"	Fellow toilet girls	**B1829**饱饱们，求助一下…真的很需要大家的经验，窝家里很穷，念完初中就没有再上学了，后面我一直在各种地方打零工，因为没有学历的缘故很难找到合适的工作…就这样工作了好几年现在攒到了一些钱想要离开这里，这笔钱不多，窝不知道该用它去学一门手艺还是就这样继续在工厂或者奶茶店上班…窝想学烘焙或者美甲，饱饱们有啥建议吗？因为去学烘焙或者美甲差不多要五千块…还是直接去烘焙店当学徒比较好呢？ **B1829:** Everyone, help. Really need some experience. My family is very poor, so much so that I left school after middle-school graduation. I have been around various places doing part-time jobs, but it is difficult for me to find a suitable job because of my education level. I have worked like this for several years, and now I have saved some money and want to leave here. Do you have any suggestions? Because I have to spend 5000 RMB to learn new skills like baking or nail art... Or is it better to directly apprentice in a bakery?
	Oppressors	**14560**為什麼 貓貓 耐耐 你們都要偏心街街？街街用你的錢買漢服 旅遊 買手機 我呢？我呢？我呢？我用的都是街街剩下的 憑什麼？我吃了街街3.5一包的榨菜 你們就罵我為什麼？榨菜就放在飯桌上 那晚街街也沒回家 我怎麼知道這個榨菜是街街的？你問我為什麼不和街街打電話問問是不是她的 我說我吃一包榨菜還要問是不是她的嗎？你又不說話了 我也把榨菜賠給了街街 給她再買了一包 回家還是摔東西發小脾氣 我到底還能怎麼做？…… **14560:** Why do you have to play favorites? My older sister uses her money to buy *Hanfu* [traditional, flashy Han clothes], travel, and buy phones, but what about me? What about me? What about me? I just live off whatever Big Sis has left. Why? Why do you scold me for eating pickles my sister bought that cost just 3.5 RMB a pack? The pickles were on the table, and my sister didn't come home that night. How would I know the pickles were hers? What else can I do?
Self-narration	Unclear	**B780**【投稿】好难过，今天在寝室室友说起卫生巾的事情，他们在感叹怎么可能有人没有用过卫生巾，还发出了嘲笑的声音甚至开起了一些不雅的玩笑，我当时表情都僵住了，可是我小时候没人管的时候时常是用不上的，所以老觉得自己生理上有疾病，也没有钱买拿纸垫过，他们没有这种经历确实不怪他们，可是我还是觉得自己以前的伤口又被撕裂开，好痛好难受。 **B780: "Contribution"** So sad. Today in the dormitory, some roommates were talking about menstrual pads. They mockingly asked, "How could someone have never used menstrual pads before?" in a laughing voice followed by some indecent jokes. I was paralyzed in the moment. When I was a child, no one took care of me, and I often couldn't use them. I even thought that I had a physical ailment that made me bleed. I didn't even have money to buy a paper pad. I won't blame them for not having had this experience, but I still feel that my wounds were torn open. Painful and hard to hear...

Appendix B

Syntactical choice with sample texts

Syntactical Choice	Example Text
No punctuation	**6421** 【贴膏】笨人是离异家庭 父母各自都有新家 在我的成长过程中不是被骂就是被打 从来没有夸奖 洗澡洗慢了被打开浴室门让别人看我妹拿我东西我教育她被骂说我天天玩手机 我真的好崩溃从好久好久之前就崩溃的要死 我受不了了向我以为会安慰我的猫猫求助结果全是说我手机游戏 在学校被同学忽视被人在本子上诅咒写我去死 我一天到晚只能哭我不知道怎么办了 我在猫猫这被后爸区别对待 我好想去死 在我第二次紫惨被发现了以后我的猫猫说我干脆一刀割。死好了 我好难受我该怎么办 **6421** "Stick" I'm from a divorced family my parents each have a new family I grew up either scolded or beaten never praised if I shower slowly they open the bathroom door to let others see my sister take my things I educated her then I was scolded that I play on my phone every day I've been really really mentally broken for a long time now I'm just going to drop dead I cannot stand to ask for help to someone I thought would comfort me the result was that they all blame me for playing mobile phone games I was ignored by my classmates at school and cursed in the yearbook I could only cry all day long I didn't know what to do I was treated so badly by my stepfather I wanted to die. Die. I feel so bad. What do I do
Immediate repetition of odd punctuation	**14500** （通过）高柱是古尔，，，效益总热衷于在劳斯童靴面前卖惨说这件事，，好绝望好想似。。😜 **14500** (passed) I am an orphan,,, my aunt is always keen to sell my miserable stories to my teachers and classmates,, I'm so desperate [and] want to die . . . 😜

✴

Investigating the Potential of a CRISPR-CAS System SARS-CoV-2 Treatment Administered Through the Nasal Passage

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Abstract

The COVID-19 pandemic ravaged the world, caused by the rapid spread of the SARS-CoV-2 virus. Vaccines and other viral treatments were quickly developed in an attempt to curb the devastation of the virus. Despite successes in developing effective viral vector and mRNA vaccines, the rapid mutations occurring in the viral genome limited the overall protection provided and administration of new vaccines was required. At the same time, pharmaceuticals were developed in an attempt to inhibit viral spread. However, their delivery methods were often intravenous or possessed a limited range of potential users due to drug interactions. This study investigates the creation of a nasal CRISPR-Cas13 system treatment to combat viral infection. A comparison between the effectiveness of CRISPR-Cas13Rx and CRISPR-pspCas13b at inhibiting viral infection through the targeting of the lung protease cathepsin L, RNA-dependent RNA polymerase, and the spike protein is made through infection and treatment of HEK293T/ACE2 cells. Success will be determined through comparison of PFU values between treated and untreated SARS-CoV-2 infected mice.

1. Background/Introduction

In December 2019, a 41-year-old patient was admitted into the Central Hospital of Wuhan, reportedly suffering from respiratory issues including chest tightness and a cough that had persisted for a week. Despite administration of antiviral and antibiotic treatments, respiratory failure ensued. Following determination of the genome sequence of the infecting virus, the strain was designated as the WH-Human 1 coronavirus (Wu et al., 2020). Quickly following this discovery, the Coronavirus Disease 2019 (COVID-19) diffused, and on March 11, 2020, the World Health Organization declared the virus to be a pandemic with alarming levels of spread and severity (World Health Organization, 2020). As of May 31, 2023, there have been an estimated 6,938,353 reported deaths globally from COVID-19 (World Health

Organization, 2023).

The causative agent of this pandemic is known as the SARS-CoV-2 virus, which specifically targets cells in the proximal airways and distal lung regions such as alveolar type 2 cells (AT2 cells) (Mulay, 2021). SARS-CoV-2 is the third documented animal coronavirus that jumped to humans in the 21st century (Coronaviridae Study Group of the International Committee on Taxonomy of Viruses, 2020). The first zoonotic coronavirus, SARS-CoV (Severe Acute Respiratory Syndrome), emerged in 2003 and rapidly spread from China to numerous nations. Over 8,000 were infected as the virus disseminated, with a fatality rate of 10% (Cheng et al., 2007). Only several years later, in 2012, another coronavirus called the Middle East Respiratory Syndrome coronavirus (MERS-CoV) exploded in Saudi Arabia with a much higher mortality rate, roughly 36% (Petersen et al., 2020). While these three viruses all target the human respiratory system, SARS-CoV-2 has a high similarity in its amino acid sequence to SARS-CoV but a low similarity to MERS-CoV (Huh, 2021). This is because SARS-CoV, SARS-CoV-2, and MERS-CoV all lie in the BetaCoV genera but both SARS viruses are found in the Sarbecovirus subgenera, while MERS-CoV is in the Merbecovirus subgenera (Kirtipal et al., 2020). However, neither MERS-CoV nor SARS-CoV were able to cause a pandemic, due to limitations in spreading between humans, and quick containment, respectively. SARS-CoV-2, on the contrary, while causing mild disease in most cases (unless an infected individual is older than 70 years of age), is significantly more infectious due to a higher transmission efficiency (Petersen et al., 2020).

The SARS-CoV-2 virus is a positive single-stranded RNA virus with 14 open reading frames (ORFs). The viral genome codes for 4 major structural proteins: the spike, envelope, membrane, and nucleocapsid (referred to as S, E, M, and N proteins, respectively). The S protein, which extrudes from the lipid envelope, is responsible for binding to the Angiotensin Converting Enzyme-2 receptor (ACE2) embedded in the plasma membrane of a lung epithelial cell. Once attached, the human transmembrane protease serine 2 (TMPRSS2) cleaves the S protein at the S1/S2 cleavage site, allowing the S2 fusogenic segment to initiate membrane fusion (Peng et al., 2021). This allows for SARS-CoV-2 entry into cells through direct fusion of the viral envelope to the host cell membrane. Another method of viral entry, which occurs when a target cell lacks sufficient expression of TMPRSS2, consists of the S protein binding to the ACE2 receptor and the entire virus-ACE2 complex being internalized through clathrin-mediated endocytosis. To diffuse viral components directly into host cell cytoplasm, cathepsins cleave the S protein at the S1/S2 site, allowing for fusion of the viral envelope to the endosome membrane unveiling the viral RNA (Jackson et al., 2022). Inside the host cell, the viral RNA genome is translated into proteins and copied into more RNA. Initially, the virus assumes the task of translating ORF1a into polyprotein 1a (PP1a) and ORF1ab into polyprotein 1ab (PP1ab). These polyproteins encode for 16 non-structural proteins, denoted as Nsp1-16, which perform vital roles in viral RNA replication, forming complex replicase machinery. These non-structural proteins provide components such as RNA-dependent RNA polymerase (Nsp12), zinc-binding helicase (Nsp13), and RNA proofreading (Nsp14). Furthermore, Nsp8 and Nsp10 play significant roles as molecular connectors, stabilizing the polymerization machinery and allowing efficient RNA replication. Through the process of RNA replication following the translation of ORF1a and ORF1ab, the positive RNA strand is copied into a complementary minus strand which serves as a template for positive viral RNA strands (Romano et al., 2020).

Assembly of the virus begins with the coating of the viral RNA in the N protein and movement into the ER-Golgi intermediate compartment (ERGIC)

where the S, E, and M are introduced and incorporated; a fraction of the ERGIC membrane is additionally incorporated, creating the viral envelope (Bai et al., 2021). Once assembled, the newly synthesized viruses traverse through the ER-Golgi pathway, where they subsequently utilize a lysosomal-dependent exocytic pathway, allowing egress from the host (Eymieux et al., 2021; Ghosh et al., 2020). This cycle repeats every time a new host cell is encountered. Due to the rapid spread of SARS-CoV-2, several preventative and therapeutic treatments have been developed with the goal of creating a stronger preliminary immune response to the virus.

As a result of the alarming dissemination of the virus throughout the world, it was critical for measures to be taken in an attempt to curb the quickly rising number of casualties from infection. Pharmaceutical companies such as Moderna and Pfizer promptly began developing vaccines under emergency approval. Soon mRNA and viral-vector vaccines began to be distributed globally for immunization. However, despite the vaccines' high protective efficacy against the Wuhan SARS-CoV-2 strain, the SARS-CoV-2 virus underwent mutations which limited the success of the original vaccines; synthesis of new vaccines was necessary to continue furthering immunity. Moreover, the most common vaccines required low temperatures of around -80° C for storage and transportation, in addition to extensive chromatographic purifications before exportation, providing additional challenges to immunization processes (Yahaya et al., 2023).

As cases of infection grew, therapeutic treatments were also developed with drugs such as hydroxychloroquine, tenofovir, sofosbuvir, and most notably remdesivir (Yan et al., 2022). Remdesivir, a broad-spectrum antiviral agent and the first FDA-approved antiviral drug for SARS-CoV-2, targets Nsp12 by incorporating into synthesizing RNA chains and prompting pre-mature terminations (Wang et al., 2020). Although remdesivir has shown a significant level of efficacy, administration methods require a 30-120 minute intravenous administration, often experienced as an uncomfortable process. An additional effective therapeutic includes the oral treatment Paxlovid, which primarily inhibits the 3C-like protease (3CLpro) Nsp5. Since Nsp5 facilitates the production of Nsp4-16, inhibiting it allows the overall inhibition of viral RNA replication. Impediment of Nsp5 occurs with Paxlovid occupying a vital enzyme active site (specifically an oxyanion hole), preventing functioning of Nsp5 (Sathish et al., 2022). The major flaw in Paxlovid is that there are numerous medications with which it interacts, such as Carbamazepine, Amiodarone, Sildenafil, Rifampin, and Eplerenone, resulting in many individuals being unable to safely utilize it as a method of treatment (National Institutes of Health, 2023). As a result of the hazardous and global nature of the COVID-19 epidemic, less traditional methods of treatment have also been explored, several of which involve the use of a CRISPR-Cas targeting system.

CRISPR-Cas, standing for Clustered Regularly Interspaced Short Palindromic Repeats-CRISPR associated proteins, is an adaptive prokaryotic immune system. This system is made up of the CRISPR-Cas locus, also known as the CRISPR array, which is 20-50 individual base pairs that repeat, occasionally interspersed with spacer sequences. Preceded by a prolonged sequence of AT base pairs (adenine-thymine pairs), spacer sequences are segments of DNA from previously invading microbes which a prokaryote cut out of the invader and inserted into its own genome. These spacer sequences provide future immune recognition for the prokaryote (Khan et al., 2018).

For a successful adaptive immune response to occur, three steps must take place. The first step involves adaptation of the prokaryotic organism through spacer integration. As previously described, alien DNA must be inserted into the genome, which is largely accomplished with the CRISPR associated proteins (Cas proteins).

The subsequent stage is referred to as CRISPR RNA (crRNA) biogenesis. In this stage, the CRISPR array is transcribed into pre-crRNA which, through the aid of Cas proteins, is processed to create crRNA. In the final stage, the mature crRNA is bound by one or several Cas proteins, forming the CRISPR-Cas effector complex also known as the Cascade (CRISPR-associated complex for antiviral defense). This complex can target invading microbes which contain a homologous sequence to the crRNA of the complex, serving as a targeting system, allowing for binding and destruction of foreign DNA or RNA.

CRISPR systems can be classified into two classes determined by the protein constituents of the effector complexes: Class 1 CRISPR-Cas effectors constitute complexes assembled from crRNA and several Cas proteins, usually between 3-6 of them; Class 2 effectors are assembled from crRNA, which may potentially be combined with another RNA named trans-activating crRNA (referred to as tracrRNA), and only one Cas protein. The role of this tracrRNA is to form a guide RNA (gRNA), which aids in specifically identifying and targeting the desired base pair sequence. However, protein systems such as that of Cas13 only have a crRNA as their gRNA. These class systems can be further divided into the following types based on composition of the Cas protein cache: Types I, III, and IV (Class 1), and Types II, V, and VI (Class 2). These types can also be divided into 30 subtypes denoted with a proceeding letter (for example: Type VI-B) (O'Connell, 2019). This antiviral defense mechanism quickly led to the idea of utilizing the CRISPR-Cas systems as a gene-editing technique. A CRISPR-Cas system could be primed against a chosen DNA/RNA sequence which would correspond to a particular gene, and once the desired sequence is identified, the system would, as in the case of the CRISPR-Cas9 system, cut the gene, terminating its expression. In order to administer a CRISPR-Cas system into the desired cells of an organism, several delivery methods have been devised, including administration through viral vectors such as lentivirus and adeno-associated virus (AAV), electroporation, hydrodynamic delivery, and lipid-mediated transfusion (Khan et al., 2018). However, in order to maximize its effectiveness, the CRISPR-Cas system must be delivered to the region containing the targeted cells as fast as possible, proving a potential problem when targeting lung cells. To combat this issue when focusing on SARS-CoV-2, treatments would have to be administered intranasally.

Two potential routes for intranasal administration have been devised, suiting two methods of delivering CRISPR systems into a cell. If a delivery vector is intended to transport CRISPR systems into designated cells, a liquid formulation containing the system would be administered through a nebulizer (air-jet, ultrasonic, or vibrating). If excipients are to deliver the CRISPR-Cas dosage into targeted cells, a powder formulation containing these excipients would be administered through a dry powder inhaler. Nebulization of CRISPR-Cas systems exhibited great success with efficient administration of plasmid DNA, mRNA, and proteins into specific cell types (Chow et al., 2020). However, general barriers to intranasal treatments still arose, as the mucus layer and ciliated cells impaired the delivery vectors by occasionally degrading them and prematurely triggering the release of CRISPR-Cas systems. Moreover, specific lung-based diseases could cause further complications should the individual develop inflamed airways with a surplus of abnormally thick mucus.

Despite these complications, CRISPR-Cas systems still appear advent-ageous to administer intranasally when paired with lipid nanoparticles (LNPs), which prove to be a promising delivery system for targeting lung regions. LNPs are a lipid-based carrier system, mainly comprised of ionizable lipids, helper lipids, polyethylene glycol (PEG) lipids, and cholesterol, all of which improve the particles'

stability, effectiveness, and payload capacity. Their miniscule size and immune avoiding properties, paired with the development of selective organ targeting LNPs, allow for the circumvention of many biological barriers. While few studies experimented with administration of LNPs carrying CRISPR-Cas complexes to respiratory regions, LNPs have been reported to successfully reach targeted lung regions and treat cystic fibrosis through intranasal inhalation (Carneiro et al., 2023; Chow et al., 2020; Robinson et al., 2018). However, altering the payload of the lipid vehicles to a CRISPR-Cas complex should likely elicit a similar level of success in circumvention of biological barriers and reaching a designated location.

More recently, the CRISPR-Cas system has been employed as a method of combatting viral infections such as SARS-CoV-2. A reprogrammed CRISPR-pspCas13b system was able to successfully target the S and N protein transcripts of the SARS-CoV-2 virus with >99% reduction of transcript levels in HEK 293 T cells and >90% in VERO cells (immortalized human embryonic kidney cells, and kidney epithelial cells extracted from an African green monkey, respectively) (Fareh et al., 2021). CRISPR-Cas13 is a Class II Type VI system which mediates RNA degradation. All six subtypes (Cas13A-D, Cas13X, and Cas13Y) of CRISPR-Cas13 are smaller than Cas9 complexes, with the Cas13 enzymes requiring a 60-66-nucleotide crRNA to ensure precision in targeting RNA (Huynh et al., 2020). Cas13 proteins adhere to two distinct ribonuclease activities (RNase): one involves pre-crRNA processing, aiding in the formation of Type VI Cascades, while the other revolves around the RNase activity in the 2 Higher Eukaryotic and Prokaryotic Nucleotide-Binding domains (HEPN domain), managing degradation of target RNA (O'Connell, 2019). CRISPR-Cas13b, typically represented as CRISPR-pspCas13b (Provotella sp. P5-125), has a size of roughly 1127 amino acids, making it the 2nd largest Cas13 subtype. With high efficiency and accuracy, Cas13b is able to successfully degrade RNA without Protospacer Flanking Site (PFS) sequence constraints (Tang et al., 2021). Yet one of the key successes of the CRISPR-pspCas13b system in combatting SARS-CoV-2 replication is its ability to tolerate up to 3 nucleotide genome mutational mismatches in the viral RNA. The significance of this discovery is that the pspCas13b complex can continue targeting the virus despite potential mutations, meaning this treatment may target a broader range of viral variants (Fareh et al., 2021).

An additional utilization of a CRISPR-Cas system to inhibit replication of the SARS-CoV-2 virus is one that aims to knock down the lung protease cathepsin L (Ctsl) messenger RNA. Ctsl is an endosomal cysteine protease that mediates the priming of the S protein, allowing viral entry through endosome membrane fusion. Knockdown of Ctsl mRNA prohibits priming of the S protein, resulting in partial inhibition of SARS-CoV-2 infection in the lungs. Such knockdown was facilitated by the CRISPR-Cas13Rx complex, which is a CRISPR-Cas13d complex from the *Ruminococcus flavefaciens* strain XPD3002 (Cui et al., 2022). The CRISPR-Cas13d complex has a miniscule size of approximately 967 amino acids with a high level of specificity and efficiency exceeding that of CRISPR-Cas13b. Its small size allows for delivery through an AAV delivery system, prompting straightforward administration (Tang et al., 2021). With administration through lung-selective lipid nanoparticles, the CRISPR-Cas13Rx Cascade has been used to successfully inhibit lethal SARS-CoV-2 infections in mice, illustrating successful Ctsl mRNA knockdown (Cui et al., 2022).

With the success of CRISPR-Cas systems in inhibiting replication of the SARS-CoV-2 virus, potential treatments revolving around CRISPR may quickly arise to provide accessible treatments that can target a broad range of variants. To ensure straightforward administration, a non-intravenous delivery system that can quickly provide a necessary dosage of CRISPR-Cas targeting complexes to specific cell types

within an individual would be ideal. Therefore, this study aims to investigate the potential of a CRISPR-Cas system SARS-CoV-2 treatment functioning through the targeting of distinct genes related to the infection and replication of SARS-CoV-2 and administered through the nasal passage.

2. Experimental Design

The investigation will be split into two distinct segments: the first will revolve around identifying the more effective existing CRISPR-Cas SARS-CoV-2 targeting system, and the subsequent one will identify the efficacy of the more effective CRISPR targeting as a treatment administered through the nasal cavity.

In the initial segment, cell cultures of a HEK293T/ACE2 cell line will be cultivated and infected with SARS-CoV-2. Following infection, several cultures will be treated with a CRISPR-Cas13 complex targeting a specific gene (either Ctsl, the D614 region of S protein, or the Nsp12 genomic region coding for viral RNA-dependent RNA polymerase (RdRp) in ORF1ab). These targets were chosen due to their critical role in the process of viral replication; targeting any of these three should greatly diminish the proliferation of the SARS-CoV-2 virus, if not completely halt it. There will be 16 groups of cultures: three uninfected (in case one well becomes contaminated or infected), three uninfected and treated with a CRISPR-Cas13Rx complex, three uninfected and treated with a CRISPRR-pspCas13b complex, one infected and untreated, three infected and treated with a CRISPRR-Cas13Rx complex, and three infected and treated with a CRISPR-pspCas13b complex. Each individual culture receiving a treatment will be administered a specific CRISPR-Cas13 complex primed against only one of the three outlined targets (Ctsl, the S protein, or Nsp12). Cell proliferation and the presence of RdRp, which plays a significant role in RNA replication, will be examined. Looking at the infected and untreated group as a baseline, the more efficient CRISPR-Cas targeting system will be identified and chosen as the sole CRISPR-Cas targeting system in segment 2. An additional comparison between cell proliferation in the uninfected groups will be considered in order to ensure that the chosen treatment complex does not inhibit the replication of cells. The most successful treatment will be utilized in segment 2.

In the second part, transgenic mice expressing the ACE2 gene will be obtained and separately housed to minimize the outside effects that could occur when the virus spreads from animal to animal. This isolation should not impose any issues, as the mice will be males who tend to have strict territorial boundaries (Kappel et al., 2019). The mice will be split into three groups for the study: one uninfected, one infected and untreated, and one infected and treated. An intranasal administration method will be devised utilizing a jet-air nebulizer, which has demonstrated past successes in administering DNA plasmids into the lungs (Chow et al., 2020). With the chosen CRISPR-Cas targeting system from part 1, a lipid nanoparticle delivery system in a PBS buffer solution diluted with distilled water will be prepared. This suspension will be poured into the reservoir of the nebulizer shortly prior to treatment of the mice. Following the construction of the delivery system, the transgenic mice will be infected with a variant of SARS-CoV-2 and left for 24 hours. After 24 hours, one group will be administered the chosen CRISPR-Cas treatment utilizing the intranasal delivery system. Symptoms and behavior will be observed, and four days after infection, the mice will be euthanized, and their lungs extracted so that a plaque assay can be used to examine the amount of viral material within the groups.

3. Methodology

Since this study will involve SARS-CoV-2 infection of cell cultures and animals, a laboratory of Biosafety Level 3 (BSL-3) and Animal Biosafety Level 3 (ABSL-3) will be used (Centers for Disease Control and Prevention, 2021). This means that access to the laboratory is restricted and always controlled, with laboratorians under medical surveillance, receiving prior immunization to SARS-CoV-2. Appropriate personal protective equipment (PPE) will be worn, and respirators are required. All work will be performed in an appropriate biosafety cabinet (BSC). Sodium hypo chloride 1000ppm will be used as a general surface disinfectant (Ağalar et al., 2020). The SARS-CoV-2 virus (in the form of the BetaCoV/England/02/2020 strain, Accession ID EPI_ISL_407073) will be kindly provided by the Biodefense and Emerging Infections Research Resources Repository (BEI Resources). The samples of SARS-CoV-2 will be stored in a buffer solution of phosphate-buffered saline (PBS) at -80˚C until viral infection of cell cultures or animals becomes necessary (Perchetti et al., 2020).

3.1 Cell Culturing (Segment 1)

To assess the efficacy of each CRISPR-Cas treatment, a HEK 293 T/ACE2 cell line (ATCC) (which expresses both CTSL and ACE2 receptors) will be used, being systematically infected with SARS-CoV-2. These cells will be cultured in Dulbecco's Modified Eagle Medium (DMEM) high glucose media (Life Technologies) containing 10% heat-inactivated fetal bovine serum, penicillin, streptomycin, and L-glutamine. A confluency of 20-80% will be maintained in 37˚C incubators with 10% of the well volume being HEK 293 T/ACE2 cells (Fareh et al., 2021).

3.2 Acquisition and Synthesis of CRISPR-Cas Targeting Systems and gRNAs

The Feng Zheng laboratory will be the supplier of the pC0043-pspCas13b crRNA backbone containing pspCas13b crRNA direct repeat sequence and two Bbsl (an isoschizomer of the site-specific endonuclease BbvII) restriction sites (Fareh et al., 2021). Custom guide RNA specifically targeting the D614 genomic region of the S protein, Nsp12, and Ctsl will be synthesized from Integrated DNA Technologies and cloned into the crRNA backbone. The following procedure outlined will largely follow methods used in the CRISPR-Cas13b targeting study by Fareh et al. (2021) and will be repeated with each targeting system individually, meaning no complex will target more than one genomic region. To clone the crRNA, forward and reverse single-strand DNA oligonucleotides (Sigma Aldrich) with CACC and CAAC overhangs, respectively, are to be annealed in annealing buffer solution (NEB buffer 3.1:H2O, 1:8.4) through incubation at 95˚C for 5 minutes and a slow cooldown in a heating block. The crRNA backbone will also be digested by BbsI (NEB) restriction enzymes for 2 hours at 37˚C and later purified with NucleoSpin™ Gel and a PCR Clean-up Kit (Thermo-Fisher Scientific) and stored at -20˚C. The digested and purified crRNA backbone will then ligate the annealed oligonucleotides (crRNA backbone: oligonucleotides, 1:3 ratio) in T4 ligation buffer for 3 hours (Fareh et al., 2021). This step should ideally be done right before administration into the cell cultures.

      The CRISPR-Cas13Rx crRNA targeting Ctsl, the D614 region, and Nsp12 will also be supplied by Integrated DNA Technologies. The Feng Zheng laboratory will also supply pXR004 CasRx pre-gRNA cloning backbone. The crRNA will be cloned

utilizing two forward and reverse oligonucleotides. Both will be annealed following the same procedure outlined in the previous paragraph; the cloning backbone will also be digested by BbsI enzymes for 2 hours at 37° C and purified in the same manner as before. A ligation reaction will take place in T4 ligation buffer for 3 hours. Once the digested and purified cloning backbone is combined with the annealed oligonucleotides in the same ratio as above (Chuang et al., 2021). As with the ligation reaction of the pC0043-pspCas13b crRNA backbone and annealed oligonucleotides, this step should ideally occur right before administration into the cell cultures.

3.3 Division and Infection of Cell Cultures with SARS-CoV-2 Variant

The cell cultures of HEK293T/ACE2 will be divided into 16 equal groups by inserting equivalent numbers of cells into 24-well plates. The groups will include three wells that remain uninfected, three wells that remain uninfected and are treated with a CRISPR-Cas13Rx complex, three wells that remain uninfected and are treated with a CRISPR-pspCas13b complex, one infected well that is left untreated, three wells infected and administered a CRISPR-pspCas13b treatment, and three wells infected and administered a CRISPR-Cas13Rx treatment. To infect, the SARS-CoV-2 variant provided, the BetaCoV/England/02/2020 strain, will first be allowed to gradually return to room temperature after being stored at -80° C. 200 µL of the virus will be inserted into the wells at a multiplicity of infection (MOI) of 0.1 in DMEM containing penicillin, streptomycin, L-glutamine, and 1 µg/mL TPCK-treated trypsin, allowing for facilitated cell entry (Fareh et al., 2021). This should be allowed to incubate at 20° C for 24 hours.

3.4 Administration of CRISPR-Cas Treatment Systems

Once the virus has incubated in the wells for 24 hours, CRISPR-Cas treatments will be administered to 6 of the 9 uninfected and 6 of the 7 infected wells. These treatments will be administered through lipid-mediated transfection (Cui et al., 2022). The transfection reagent Lipofectamine MessengerMAX (Thermofisher Scientific) will be diluted in OptiMEM™ Medium (MessengerMAX: Medium, 1: 2) and then combined with one of the CRISPR-Cas systems (1:1) and incubated at room temperature (20° C) for 30 minutes. This will be repeated for each of the 6 total CRISPR-Cas13 treatment complexes. These complexes should be CRISPR-Cas13Rx targeting Ctsl (RxCtsl), CRISPR-Cas13Rx targeting the D614 region (RxD614), CRISPR-Cas13Rx targeting Nsp12 (RxRdRp), CRISPR-pspCas13b targeting Ctsl (pspCtsl), CRISPR-pspCas13b targeting the D614 region (pspD614), and CRISPR-pspCas13b targeting Nsp12 (pspRdRp). The appropriate amount of the transfection complexes will be determined and added to a designated cell culture. Following this step, there should be three wells left uninfected, six uninfected and treated (one each with RxCtsl, RxD614, RxRdRp, pspCtsl, pspD614, and pspRdRp), one infected and untreated, and six infected and treated (one each with RxCtsl, RxD614, RxRdRp, pspCtsl, pspD614, and pspRdRp). The cells will incubate for 48 hours.

3.5 Quantitative Analysis of the Inhibition of SARS-CoV-2 by the CRISPR-Cas Treatments

In order to determine the extent of cell proliferation, a cell viability assay (Resazurin Reduction assay) will be conducted, in which resazurin is dissolved in the medium and reduced by cells with active metabolism into a resorufin product, turning a shade of pink (Riss et al., 2013). To measure viral replication, a reverse transcription

quantitative polymerase chain reaction (RT-qPCR) will be carried out, analyzing all three infected wells. Viral RNA will be extracted utilizing a QIAamp Viral RNA Mini kit (Qiagen) and converted into cDNA with a SensiFast cDNA kit (BioLine). The RT-qPCR reaction, targeting the RNA-dependent RNA polymerase gene, will occur in a Mx3005P QPCR System (Agilent) using PrecisionFAST qPCR Master Mix (Integrated Science) (Fareh et al., 2021). The results of the RT-qPCR will be compared, utilizing the data from the well that was left infected and untreated as a baseline. Comparisons between the cell proliferation that occurred in the uninfected groups will be made to examine whether the treatments negatively impacted the growth of cells. Whichever CRISPR-Cas targeting system results in the lesser amount of viral RNA matter (signifying that SARS-CoV-2 viral replication was inhibited) and has minimal negative impact on cellular proliferation will be the system of choice for the subsequent segment of the investigation.

3.6 Acquisition of Transgenic Mice (Segment 2)

In order to ensure the infection by SARS-CoV-2, transgenic mice expressing human ACE2 receptors under control of cytokeratin 18 promoter K18-hACE2 (7-8 weeks of age, male) will be used (Jackson Laboratory). This type of transgenic mice was specifically chosen, as the K18-hACE2 promoter will aid in facilitating SARS-CoV-2 infection. They will be maintained on a 12-hour light/dark cycle with food and water and in a room of 22.5° C with a humidity of 51% (Cui et al., 2022). Transgenic mice will be kept separate from one another to minimize external factors. The mice will acclimate for seven days prior to experimentation.

3.7 Creating a Nasal CRISPR-Cas Treatment

To more effectively administer the CRISPR-Cas treatment, a lipid-nanoparticle delivery system will be devised. This lipid nanoparticle (LNP) system will then be transferred into a PBS buffer which will then be diluted with distilled water and inserted into a jet-nebulizer. Lipid nanoparticles will be synthesized by mixing DLin-MC3-DMA (MedKoo Biosciences), DSPC (Avanti Polar Lipids), cholesterol (Sigma), DMG-PEG2000 (NOF America Corporation) and DOTAP (Avanti Polar Lipids) (25:5:19.3:0.8:50 ratio respectively) in ethanol with CRISPR-Cas13 complex in a citrate buffer (final weight ratio of lipid:RNA should be 20:1) (Cui et al., 2022). Utilizing a pipette, 5 milliliters of lipid-CRISPR solution will gradually be inserted into 5 milliliters of PBS buffer, allowing for assembly of the lipid nanoparticles. They will be stored at 4° C for 10 days to ensure proper encapsulation. During incubation, the nanoparticles will be monitored with aliquots being taken every other day to test encapsulation efficiency, which can be done by a RiboGreen assay (ThermoFisher Scientific) and Spectra Max M3 (Molecular Devices) with SoftMax pro6.4 (Cui et al., 2022).

Following complete encapsulation, the solution will be mixed with distilled water to assist the nebulizer in generating aerosol particles from a liquid suspension (1:1 ratio). This will then be inserted into an Aerotech II jet nebulizer (Aerotech Inc), which will facilitate intranasal delivery to the lungs (Chow et al., 2020).

3.8 Grouping Transgenic Mice and Infecting with SARS-CoV-2

There will be three distinct groups in this segment of the study: one with six uninfected mice, one with six infected and untreated mice, and one with six mice infected and administered the nasal CRISPR treatment. For infection of the

designated groups, the transgenic mice will be lightly anesthetized with isoflurane and infected with 105 plaque forming units (PFU) of the SARS-CoV-2 variant (this amount could be determined through a plaque assay on the supply of the variant). Viral infection will be allowed 24 hours to culminate (Cui et al., 2022).

3.9 Administration of CRISPR-Cas Treatment

24 hours post infection, the third group of transgenic mice will receive CRISPR-Cas treatment. 1 mL of the LNP suspension will be dispensed by the nebulizer in a nose-only exposure chamber to each mouse of group 3 individually.

3.10 Analyzing the Efficiency of the Nasal CRISPR-Cas Treatment

Throughout the experiment, data concerning the state of the mice will be collected, which will include weight, temperature, number of deaths within the groups, and behaviors such as ruffling fur and hunching. Symptoms such as sneezing, labored-breathing, nasal discharge, and lethargy will also be considered. Humane euthanization will occur should weight loss exceed 20% or the mouse in question becomes moribund. Once the surviving mice pass four days post infection (DPI), the mice will be humanely euthanized, and the lung tissue will be collected and homogenized in preparation for tissue virus titer by plaque assay (Cui et al., 2022). The homogenate will be fixed in formaldehyde and the cells stained with propidium iodide to properly visualize plaque formation. Utilizing a phase inverted fluorescence microscope (AmScope), the plaque will be counted, revealing the PFU of the lung tissue. The PFU result of the mice infected and treated with CRISPR will be compared to that of the untreated group. The total deaths of the groups and scale of symptoms will be taken into consideration, with the uninfected group's data as the baseline comparison.

4. Discussion

It is expected that the PFU value of the mice treated with the CRISPR-Cas targeting system therapeutic will be lower than that of the untreated group, illustrating the inhibition of viral replication. This will suggest that the methods for developing treatments against viral infections such as that of influenza and Ebola will broaden. In the realm of SARS-CoV-2, a more effortless and faster therapeutic treatment method will allow more efficient treatment against deadly infection in a non-intravenous manner. This method of treatment will be available to a broader range of people, bypassing the limitations of Paxlovid and the unappealing nature of the intravenous delivery system of remdesivir. Furthermore, this nasal treatment directly targets the lung, which is known to be the primary destination of the SARS-CoV-2 viral infection, meaning that potential recovery times could be faster as the treatment promptly arrives at its objective. However, this nasal treatment could also potentially serve as a preventative as well, if administered regularly prior to infection.

In the realm of CRISPR technologies, success would demonstrate the feasibility of a CRISPR therapeutic, adding to its potential as a treatment for more severe infections and diseases such as types of cancer, HPV, HIV, Rabies, and Ebola. Additionally, success would provide further data about a less-tested delivery method that could prove beneficial in treatment of diseases such as lung cancer and cystic fibrosis. Success would further prompt considerations regarding the longevity of the CRISPR treatment once administered. Despite initial inhibition of viral replication, CRISPR-Cas13 complexes often have been found to diminish in efficacy following 24

hours after administration, especially when vigorously combatting pathogens (Cui et al., 2022; Fareh et al., 2021). Therefore, setting an administration frequency that maximizes treatment efficacy would be an important next step. Whether society is ready for it or not, as more and more successful applications of CRISPR-Cas technology are exhibited, a future of CRISPR treatments grows nearer.

However, should the study find that the PFU value is greater or equal to that of the untreated group, then this investigation will demonstrate the limited ability of CRISPR treatments as of this moment. Of course, extraneous factors that impacted the experiment will be considered in addition to the limitations of methods and their respective accuracies and potential human error. CRISPR-related treatments against viral infections and diseases will have to be further studied and advanced prior to consideration for public medical use. Furthermore, the study would demonstrate that a nasal method of administration is not yet suitable for a SARS-CoV-2 treatment in the way it has been developed through this investigation. Nonetheless, it should be noted that intranasal delivery methods of CRISPR have been demonstrated to work and therapeutic treatments against several viral and bacterial infections have been successfully tested and demonstrate little adverse effect; for this reason, a potentially refuted hypothesis of this investigation does not signify the failure of CRISPR as a whole, but rather, a potentially flawed experiment, method of delivery, or approach to administering the treatment. Even in the face of a failure to inhibit viral replication of SARS-CoV-2, CRISPR-Cas treatments still hold potential in this field of viral therapeutics, predicting their potential application in the near future with more development.

Of great importance is the long-term safety of this treatment. As the transgenic mice will be examined for only a brief period, the feasibility of such a treatment over a lengthy period of time remains unknown. However, as this method of combatting viral infection is relatively new, such information is sparse and more studies are required in order to solidify the knowledge regarding CRISPR-Cas's safety as a treatment.

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Predictive Modeling of Nucleoside Analog-Induced Antiviral Resistance Mutations in SARS-CoV-2

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Abstract

As the Covid-19 pandemic spreads, infecting millions of people, antiviral drugs targeting the Sars-CoV-2 virus are being developed. Among these approaches are nucleoside analogs, which target viral RNA synthesis by stopping the function of viral RNA-dependent RNA polymerase (RdRp). However, current nucleoside analogs run the risk of being cleaved by the nsp14 exonuclease (nsp14-exoN); nsp14-exoN removes the nucleoside analog from the synthesized RNA and rescues the RdRp. Nsp14, on the other hand, requires nsp10 to reach its full functionality. Thus, nsp14-nsp10 interaction is a significant factor that determines the efficacy of antiviral drugs. This paper proposes three methods, to be conducted procedurally, to analyze the effects of potential mutations on the functionality of the three proteins. Sites with high mutability are identified with the non-synonymous to synonymous substitution ratio (πn/πs ratio) and Shannon entropy. Once those sites are identified, mutations are generated on currently available *in silico* protein models to analyze their effect on nsp14-nsp10 interactions. An additional *in vitro* study involving site-directed mutagenesis is proposed both to verify the *in silico* methods and to test the antiviral resistance in mutated viruses.

1. Introduction

As a response to the widespread devastation of the Covid-19 pandemic, the severe acute respiratory syndrome coronavirus 2 (Sars-CoV-2) virus quickly became one of the most studied viruses. At the latest count, a total number of 8.2 million sequences have been submitted to the NCBI Virus Sars-CoV-2 datahub. Data availability enables large-scale *in silico* studies on the sequence of the virus from an evolution biology approach, whose significance is further stressed by the potential biological and social devastation of research with real viruses.

The Sars-CoV-2 virus constitutes plus-strand single-strand RNA (+ssRNA) encapsulated by the nucleocapsid (N) protein (Wang et al., 2020). The Sars-CoV-2 virus has the same structure as overall coronaviruses. Outside the nucleocapsid

protein, a membrane made up of the membrane (M) protein, the spike (S) protein, and the envelope (E) protein are present (Brian and Baric, 2005).

To initiate an infection, the spike proteins on the viral envelope bind to the angiotensin-converting enzyme 2 (ACE2) protein present on human epithelial cell surfaces (Hoffmann et al., 2020). The viral envelope fuses with the cell membrane, and viral RNA is injected into the host cell cytoplasm. Upon cell entry, the viral RNA serves as mRNA for the translation of the open reading frame (ORF) 1a and ORF1b, producing polyproteins pp1a and pp1ab (Wu et al., 2020). The polyproteins are cleaved by viral proteases, and the resultant 16 non-structural proteins (NSP) are released into the cytoplasm (Malone et al., 2022). Translation of the host cell is inhibited by nsp1 (Thoms et al., 2020), while nsp12, nsp13, nsp14, and nsp16 assemble to form the holoenzyme RNA-dependent RNA polymerase (RdRp) (Malone et al., 2022). Other nsps assemble into the replication-transcription complex (RTC) and reside in membrane structures derived from the rough endoplasmic reticulum (Hartenian et al., 2020). New viral RNA is produced at the replication-transcription complex (Romano et al., 2020), which eventually translates into 4 structural proteins, 6 accessory proteins, and 16 non-structural proteins (Malone et al., 2022). After replication and translation, viral protein and genome assemble into a new virus, completing the virus life cycle. Of the 16 non-structural proteins, nsp10, nsp12, and nsp14 are the focus of this study.

Nsp12 is the subunit RdRp that catalyzes RNA synthesis. The RdRp on its own does not include an exonuclease unit for proofreading, and RdRp alone has a low fidelity of 10-4 to 10-6 substitutions per nucleotide per round (Moeller et al., 2022). Nsp14 is a bifunctional protein, with the C-terminal a guanine-N7-methyltransferase (N7-MTase) and the N-terminal a 3'-to-5' exonuclease (Chen et al., 2009). The nsp14-exoN proofreads newly synthesized RNA, correcting the RdRp when it makes a mistake. Nsp14 interacts closely with nsp10, relying on nsp10 to be fully functional. Stable nsp14-nsp10 interactions are crucial for exonuclease activity, which reaches a maximum when nsp14 and nsp10 are present in a specific ratio (Saramago et al., 2021).

Thus, analyzing and predicting the effect natural selection has on the interactions between nsp14 and nsp10, with respect to each other and with respect to RdRp, is crucial for predicting the development of antiviral resistance.

This study aims to predict the effect of natural selection on nsp14 and nsp10 in three steps: 1) predict sites where mutations are more likely to be tolerated (referred to as mutability for simplicity); 2) analyze protein structures and protein-protein interactions; 3) measure antiviral resistance on a mutated virus. Step 1 and step 2 are done with *in silico* methods (computer simulation), while step 3 is an *in vitro* experiment involving site-specific mutagenesis proposed to measure RdRp fidelity, also serving as a verification of the computer models. Sars-CoV-2 genome sequencing data will be downloaded from the NCBI Virus Sars-CoV-2 Data Hub, and to reduce computational effort, randomized subsets of the complete dataset will be used.

Whether a site has high mutability or not is determined by the diversity of nucleotides at that site exhibited in the dataset. Diversity is measured in two ways: the non-synonymous to synonymous nucleotide diversity ratio ($\pi n/\pi s$ ratio) (Li et al., 2016) and Shannon entropy (Shannon, 1948). With a reference sequence, a nucleotide is marked "synonymous" if substitution at the nucleotide does not change the amino acid as coded in the reference sequence; it is "non-synonymous" if substitution at the nucleotide changes the coded amino acid. πn is the number of non-synonymous nucleotides, while πs is the number of synonymous nucleotides. In general, the $\pi n/\pi s$ ratio measures the selective pressure on a sequence: $\pi n/\pi s >$

1 implies positive selection, πn/πs = 1 infers neutral selection, and πn/πs < 1 infers purifying selection (Braun et al., 2023). The Shannon entropy measures the diversity of a given input, and is higher for diverse inputs, making Shannon entropy a good indicator for measuring the diversity of nucleotides at a certain site.

To predict the effects mutations have on viral fitness, the algorithm PyR0 (Obermeyer et al., 2022) is used. PyR0 is a machine learning approach, trained on Sars-CoV-2 data, to predict transmissibility based on an input genome sequence. Similarly, *in silico* protein-protein interaction analysis is proposed to analyze the interactions between mutated viral proteins, namely between nsp14 and nsp10 and between nsp14-exoN and RdRp.

Finally, an *in vitro* study involving site-directed mutagenesis is proposed to test whether the mutations help viruses develop antiviral resistance or not. Substitutions on chosen sites are produced with site-directed mutagenesis. Ritonavir-boosted nirmatrelvir, remdesivir, and molnupiravir are chosen to be tested, based on the NIH Covid-19 Treatment Guidelines for therapeutic management (accessed from https://www.covid19treatmentguidelines.nih.gov/).

In summary, *in silico* analysis is used, on both nucleotide level and protein level, to identify sites where mutations are likely to be tolerated. After identifying the sites, *in silico* PPI analysis and site-directed mutagenesis are used to analyze the impact the mutations have on protein functionality, eventually analyzing the potentiality of the virus developing antiviral resistance.

2. Experimental Design

To predict favored mutations, sites on the genome that are likely to mutate must first be identified. In this study, the non-synonymous to synonymous ratio (πn/πs ratio) and Shannon entropy are implemented with a sliding-window approach, resulting in a continuous graph plotting selective pressure along the genome sequence. Regions with high πn/πs ratios indicate positive selection, whereas regions with low πn/πs ratios undergo purifying selection and are excluded from this study. Shannon entropy complements the πn/πs ratio, which, again, is a calculation of diversity at each position. The two methods are employed specifically on the sub-sequence that codes for nsp10 and nsp14.

Since sequences downloaded from the database are not annotated, the exact locations of the sequence that codes for nsp14 and nsp10 are not known. Therefore, the locations are approximated with the locations of the two proteins on an obtained annotated sequence.

The reference sequence provided in the NCBI Virus Sars-CoV-2 datahub (taxid: 2697049) is used as the reference for the calculation of the πn/πs ratio. Before implementing the sliding-window approach, the sequences in the dataset must first be aligned. This alignment is achieved with the Clustal Omega (Slevers et al., 2017) multiple sequence alignment (MSA) algorithm.

Once sites with high nucleotide diversity are identified, computer sequence data are randomly modified on those sites to mimic random substitutions. The modified data is to be inputted to the PyR0 algorithm to predict the effects of the random substitutions on viral fitness. Sites that produce the most tolerated mutations are recorded.

3. Materials and Methods

3.1. Predict Favored Mutations

3.1.1 Identify Sites of Interest

Sites of interest are those where mutations are likely to be tolerated. Based on natural selection, mutations that occur on conserved sites are likely to be deleterious, and mutations that occur on divergent sites are likely to be tolerated (although mutations being tolerated is not equivalent to mutations being beneficial). Thus, the diversity of nucleotides at a given site is an important indicator of the mutability of the site. The diversity of nucleotides at each site is calculated to predict mutation tolerance at each site. By calculating the diversity at each site on the genome, sites where mutations are likely to be tolerated can be identified.

Each sequence in the database is compared to a given reference sequence, producing a single πn/πs ratio. In this study, the πn/πs ratio is implemented with a sliding-window approach. This approach requires two empirically determined parameters. The sliding-window approach works iteratively, where a "window" with a length of l, shorter than the original sequence, is placed on both of the sequences. Once the πn/πs ratio is calculated, both windows slide s nucleotides in the same direction, and a πn/πs ratio is calculated for the new windows. The calculated πn/πs ratios are aligned with their respective window position, building up a continuous graph that estimates nucleotide diversity at each site. Theoretically, parameters l and s could be any positive integer smaller than the sequence length in the dataset. Under the context of nucleotides and codons, the stride s would only make sense as a multiple of three, since three nucleotides make up a codon. Window length l must also be chosen carefully. As the validity of πn/πs ratios increases with input sequence length, large values of l would produce reliable πn/πs ratios but provide less information about the site that is being calculated.

Shannon entropy measures the amount of "information" contained in a given input by comparing the occurrence of each unit value. As an example, in an English sentence, unit values refer to the 26 English alphabet characters. Under the context of nucleotide diversity, unit values are the four nitrogenous bases. When each nitrogenous base makes up 25% of the database, Shannon entropy reaches a maximum when the occurrence of each unit value is the same; it reaches a minimum when only one single nitrogenous base occurs in the input. Given a chosen nucleotide position in a sequence database, Shannon entropy H is calculated as:

$$H = \sum_{i}^{s} -p_i \log p_i$$

where $S = \{A, C, T, G\}$, the four nitrogenous bases, and p_i is the likelihood of finding nitrogenous base i in the given position (Shannon, 1948). Positions with high entropy values are divergent throughout the database, so mutations that occur in positions with high entropy values are more likely to be tolerated. In this study, to reduce noise in the data, Shannon entropy is also implemented with a sliding-window approach. The average entropy value within a window is used.

Both approaches, the non-synonymous to synonymous ratio and Shannon entropy, calculate the diversity of each position by analyzing the nucleotides at that position in the database. It is crucial to ensure that the sequences are properly aligned so that sites in different sequences occur in the same location. In this study, Clustal Omega will be used to align the sequences in the database. Clustal Omega is

available as an online tool (https://www.ebi.ac.uk/Tools/msa/clustalo/). By employing MSA on the dataset, the same site in different sequences could fortunately be placed in the same position, enabling direct comparison between different sequences.

The output of both approaches is a continuous graph, assigning each position on the sequence a score (referred to as "mutation score" in sections below for convenience) that estimates the likelihood of a mutation occurring on that position to be tolerated. For both approaches, the higher the score, the more likely the position is going to embed tolerated mutations. To ensure the feasibility of the output of this section, the positions of sites with high mutation scores are compared to the positions of currently identified active sites of the two proteins of interest (specifics are included in section 3.2). Sites with high scores are chosen to be further studied in the next section

3.1.2. Predict Effects of Random Mutations

Effects of random mutations are predicted by using the PyR0 algorithm. PyR0 is a machine-learning algorithm trained upon 6.4 million Sars-CoV-2 genome sequences, and it predicts viral reproduction number (R_0) based on its genome. In this study, R_0 serves as the primary indicator for viral fitness.

Random substitutions are generated at sites of interest that are identified using methods proposed in section 3.1.1. Since the PyR0 approach requires the complete viral genome to make predictions, several sample sequences are randomly chosen to embed the generated random substitutions. Substitutions are generated on the chosen sequences and serve as the input for the PyR0 program, and a fitness score is assigned to each nucleotide position. The fitness score α is defined as:

$$\alpha = \sum_{j=1}^{n}\left(\sum_{i}^{S}(R_o - R_{i,j})\right)$$

where $S = \{A, C, T, G\}$ is the set of potential nitrogenous bases (before and after substitution) at a given position, R_0 is the fitness indicator for the original sequence, $R_{i,j}$ is the fitness indicator of the sequence after a substitution to nucleotide I of the jth sequence, and n is the number of sample sequences. Ideally, large n values would increase the validity of α, but compromises could be made with respect to the amount of computational resources available.

The fitness score of a certain site is defined to be the summation of α scores of each nucleotide within the site. Sites with the highest fitness scores would be identified as key sites for further *in vitro* and *in silico* analysis.

3.2. Protein-Protein Interaction Analysis

With key sites for mutations identified, this section explores the functional significance of substitutions occurring at these sites with *in silico* Protein-Protein Interaction (PPI) tools, focusing on two interactions: nsp10-nsp14 interactions and nsp12-exoN interactions. Studying the two interactions provides knowledge about exonuclease activity, and how it impacts RNA synthesis.

To avoid ambiguity in protein folding algorithms, this section assumes that point mutations do not drastically alter protein structure and function; the protein structure after a single point mutation remains in large parts similar to the structure before mutations. Currently available protein models of nsp14, nsp10, and RdRp are used. Key sites on the protein models are modified (as by point mutations) to explore

the potential effects mutations have on protein-protein interactions.

Once a set of mutation-favorable sites are identified, the functions of the sites are examined manually. With a given protein model, the corresponding locations of mutation-favorable sites are identified in the model. The interactions and functionality, before and after mutations, of each site are examined manually.

3.3. *In Vitro* Studies

An *in vitro* experiment is designed to measure the impact the mutations had on enzyme function and to verify the results produced by computer algorithms. Site-directed mutagenesis is conducted to generate specific mutations at desired sites. The mutated viruses are used to infect cells, and the efficacy of the three nucleoside analogs, ritonavir-boosted nirmatrelvir, remdesivir, and molnupiravir, are tested.

3.3.1. Generating Mutations

The genome will be modified and assembled back into Sars-CoV-2 virus with the circular polymerase extension reaction (CPER) based on the method of Torii et al. (2021). Recombinant viruses are produced by transfecting a plasmid containing the clone DNA (cDNA) of the viral genome into the host cell.

Sars-CoV-2 virus with known genomic sequence will be obtained from the BEI Resource Repository. Viral RNA will be isolated using the EZ Tissue/Cell Total RNA Miniprep Kit (EZ BioResearch). The first cDNA will be produced using the PrimeScript RT Reagent kit (Takara Bio) with random primers, following the manufacturer's instructions. Fragments of cDNA with overlapping ends are produced, covering the entire viral genome.

Site-directed mutagenesis will be conducted on the cDNA fragments to induce substitutions in desired locations. The sequence of the cDNA fragments will be obtained from Qiagen. PCR is conducted to amplify the fragments, with primers designed from the obtained sequences.

Circular polymerase extension cloning (CPEC) will be conducted to assemble the cDNA fragments into a plasmid containing the complete viral genome, following the method of Quan et al. (2009). Overlapping cDNA fragments are assembled by polymerase cycling assembly (PCA). Five cycles of PCA are conducted with the overlapping cDNA fragments with Phusion High-Fidelity Master Mix (Thermo Science), following the cycle of denaturing, annealing, and extending. Under the same setting, an empty linear vector is added, and CPEC is conducted with the same denature-anneal-extend cycle. When annealing, the overlapping ends of neighboring fragments first anneal with each other and serve as the primers for the extension reaction (Edmonds et al., 2013). The product of CPEC is plasmids containing the cDNA of the complete viral genome, in the correct order.

The obtained plasmid will be transfected into host cells using the TransIT-LT1 Transfection Reagent (Mirus Bio), following the manufacturer's instructions. After transfection, the cDNA will be transcribed and translated into viral proteins, yielding new viruses.

3.3.2. Assay Antiviral Resistance

Viruses will be divided into the mutated experimental group (conducted site-directed mutagenesis) and the non-mutated control group. Each group is further divided into 2 batches, with one batch receiving nucleoside analogs and the other batch not.

Nucleoside analogs and viral particles are introduced with the method of Choy et al. (2020). Cells are pre-treated with diluted antivirals for 1 hour before the virus is introduced at MOI=0.02, which means that for every 100 cells studied, two

viral particles will be introduced. The cells will be incubated for 2 hours in the presence of both the virus and the antivirals before the virus alone is removed. Cells will be then incubated for 48 hours in the presence of diluted antivirals. After incubation, supernatants will be collected, and viral loads will be measured with quantitative real-time RT-PCR (TaqMan Fast Virus 1-Step Master Mix).

For each group, nucleoside analog efficacy is compared between the batch with nucleoside analogs and the batch without nucleoside analogs. The virus will be considered to have developed antiviral resistance if nucleoside analog efficacy for the experimental group is lower than that of the control group.

4. Discussion

The ultimate goal of the proposed study is to predict the potential of Sars-CoV-2 to develop antiviral resistance against current nucleoside analogs. Specifically, the possibility of nsp14-exoN developing the ability to cleave out nucleoside analogs is investigated. By studying the Sars-CoV-2 genome at both the nucleotide level and the protein level, this study aims to map mutations to a potential change in protein structure and eventually to viral fitness. This proposal is a direct attempt to bridge the gap between mutability and viral fitness by considering protein structure and functionality.
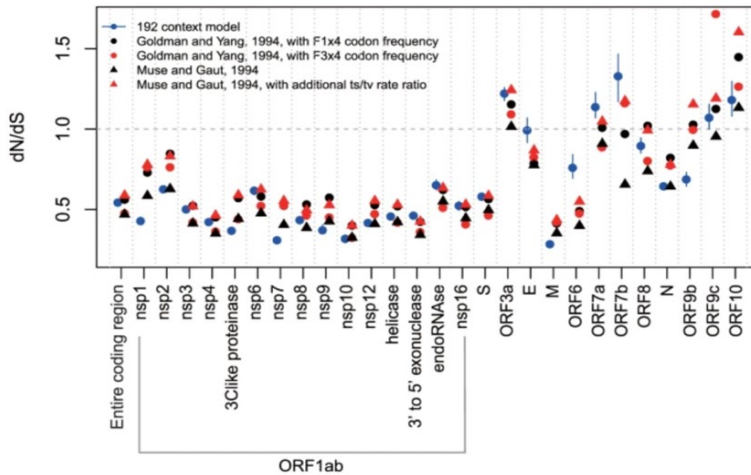
By studying the effects of potential mutations on nsp14 and nsp10, insights into antiviral resistance could be gained. Current nucleoside analogs run the risk of being cleaved by the nsp14 exonuclease (nsp14-exoN), in which nsp14-exoN removes the nucleoside analog from the synthesized RNA and rescues the RdRp. Nsp14-exoN activity is crucial to the virus's sensitivity to nucleoside analogs (Moeller et al., 2022). Thus, studying mutations of nsp14 and nsp10, the protein that helps nsp14 reach its full functionality, is crucial to the understanding of the virus developing potential antiviral resistance.

In this proposal, metrics (the $\pi n/\pi s$ ratio and the Shannon entropy) that are commonly used to measure the mutability of a specific site are used to locate sites with high mutability. The $\pi n/\pi s$ ratio and the Shannon entropy are not the only feasible metrics for this approach; instead, any metric (such as the dN/dS ratio or nucleotide diversity π) could be used, based on the interest of the user. However, the decision to choose which metric to use should not ignore the limitations posed by the sliding-window approach. Because calculations are done within a "window", the sequence length for each calculation is constricted by the window size. Thus, metrics that are sensitive to input sequence length are not ideal for the approach. Moreover, the sliding-window approach poses an extra level of computational expense (linearly related to the input sequence length), so large-scale machine learning models are not ideal to be used directly in the sliding-windows. One reason that this proposal chooses the $\pi n/\pi s$ ratio and the Shannon entropy is that they work on single nucleotide levels and are computationally inexpensive to calculate. Thus, balancing between window size and the complexity of the metric is essential for producing viable results.

Similar to the metrics, the sliding-window approach is not confined to use upon nsp14 and nsp10. Other proteins, open-reading frames, or even the entire viral genome could be studied using this method. Genome fragments that are more divergent are more guaranteed to produce viable results than other fragments that are more conserved. Assessment of the synonymous substitution ratio (dN/dS ratio) for each protein coded in the Sars-CoV-2 genome (Yi et al., 2021) suggests that selection on ORF1ab is purifying. Depending on the diversity of the ORF studied, the

obtained results could be different by a large margin.

Figure 1. *The conservation (dN/dS) of each protein*

Protein-protein interaction (PPI) analysis and site-directed mutagenesis are two approaches to studying the effect of potential mutations on viral function. In the PPI analysis, employing multiple algorithms to minimize error in each singular algorithm is better. This study uses currently available protein models to retain simplicity and avoid ambiguity in protein folding; mutations are examined on the currently available protein models. However, with the use of AI tools, such as AlphaFold (Jumper et al., 2021), a sequence with mutations could be folded from scratch.

To fit the goal of this study, antiviral resistance is measured after conducting site-directed mutagenesis. Other assays could be used to test out different aspects of viral function. Nonetheless, studying antiviral resistance in an *in vitro* study necessitates reconsiderations regarding bioethics. Even if most generated mutations remain largely neutral, conducting the *in vitro* experiment faces the risk of generating a mutant virus that is resistant to current therapeutics.

Overall, the method proposed in this paper is versatile and does not have to be constricted to the interest of this proposal. The general procedure of predicting mutations, conducting PPI analysis, and conducting site-directed mutagenesis could be applied to any interest, not only antiviral resistance.

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Reinterpreting Architectural Heritage: Reflecting the Past and Shaping the Future in the Adaptive Reuse of Columbia Circle

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Abstract

Adaptive reuse has gained impetus in recent years as a sustainable approach that lengthens the life of historic buildings while ensuring they are compatible with the demands and values of modern society. Situated in Shanghai's Xinhua Road historical neighborhood, Columbia Circle became one of Shanghai's most high-profile adaptive reuse projects upon its completion in 2018. The diverse colonial and industrial past lives of Columbia Circle provided fertile soil for its transformation into a vibrant cultural hub with creative offices, shops, and restaurants but also raised questions surrounding the adaptive reuse of historical heritage. How should we balance preservation and rehabilitation? Is the reinterpretation of historic heritage ever justifiable? Past research often focuses on physical and material changes accompanying adaptive reuse but neglects social and cultural transformations. This paper discusses Columbia Circle's adaptive reuse through a cultural lens and argues that the daring reinterpretation of identity extricated the site from the constraints of its historical connotations of exclusivity. Changes in the interactions and perceptions associated with Columbia Circle forged a new inclusive, open, and tolerant space that has become central to fostering community wellbeing and cohesion. Beyond the surface-level changes, this intrinsic change engendered Columbia Circle's economic and social success. This paper explores theoretical perspectives, architectural rehabilitation, and spatial reorganization to present Columbia Circle as a testament to Shanghai's introspection of its conflicting past and a microcosm of its future ambitions.

1. Introduction

The adaptive reuse of Columbia Circle is a powerful example of how the troubling historical connotations of heritage can be reframed as motivation for growth. Located in the Xinhua Road historical neighborhood of Shanghai's Changning district, Columbia Circle was revitalized as a public space in downtown Shanghai in 2016 (Figure 1).


Figure 1. *Map showing the location of Columbia Circle in the western part of downtown Shanghai. Columbia Circle is located in the Xinhua Road historical neighborhood, designated a "historical landscape preservation zone" by the Shanghai government (source: modified figure by author based on image from Google Earth, 2023).*

Presently, the site is centered around three main historic buildings—the Columbia Country Club, the Navy Club, and Sun Ke Villa—and complemented by several industrial buildings formerly part of the Shanghai Institute of Biological Products to provide retail, cultural, and creative office space (Figure 2).
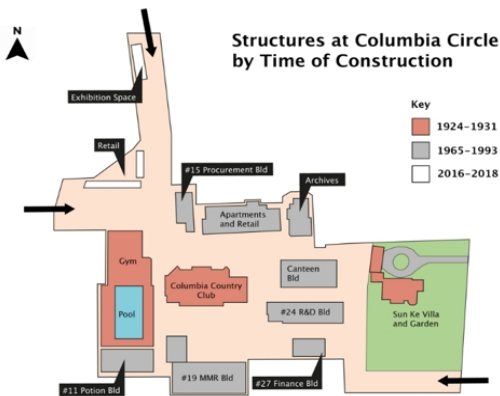
Figure 2. *Map by author showing the overall layout of Columbia Circle. There are three predominant types of structures at Columbia Circle, corresponding to the colonial, industrial, and modern eras. Of these structures, only those constructed during the colonial era enjoy state protection.*

The history of Columbia Circle before its adaptive reuse has two distinct stages, corresponding to former occupants of the site. The first stage spanned from 1920 to 1945, during the international settlement era of Shanghai, and the second stage spanned from 1950-2016, during which Columbia Circle was used as an industrial site (Figure 3).
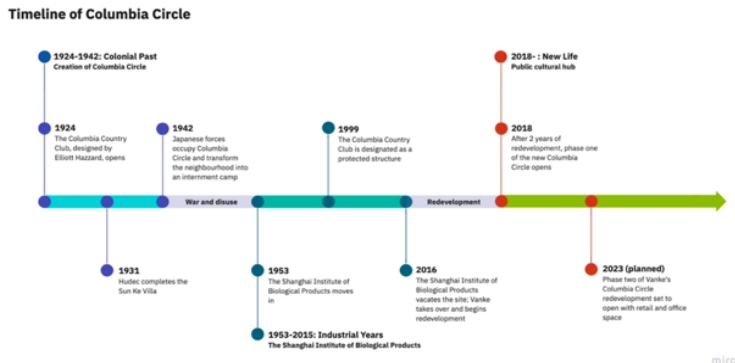
Figure 3. *Timeline by author of Columbia Circle. Columbia Circle's history can be divided into two distinct periods: colonial and industrial. Each era of usage imparts unique architectural heritage to the complex.*

The origins of Columbia Circle stem from the 1920s. A significant number of foreign nationals resided in the international settlements of Shanghai under the jurisdiction of the Municipal Council. In 1924, the Municipal Council constructed Columbia Avenue and Amherst Avenue, extending it beyond the boundaries of the international settlement into the outskirts of Western Shanghai. [1] This road extension encouraged the Columbia Country Club to move from its location on Route Doumer to the South of the Great Western Road, adjacent to the newly opened roads. [2] Elliott Hazzard was tasked with designing the new Columbia Country Club, which opened in the same year.

The Columbia Country Club spurred many new developments in the area. The Raven Trust Company invited renowned architect Laszlo Hudec to design villas for the quiet, suburban neighborhood that would become known as Columbia Circle. In 1931, Hudec's villa for Sun Ke (Sun-Yat-Sen's son) was also completed adjacent to the Country Club.[3] The amalgamation of country clubs and exclusive villas catering to the international population in pre-WW2 Shanghai would continue until 1942, when Columbia Circle was occupied by Japanese forces and transformed into the Lincoln Road Concentration Camp for international citizens.[4]

After the communist revolution, Columbia Circle took on a new industrial role. [5] In 1953, Mayor Chen Yi directed the Shanghai Institute of Biological Products (SIBP) to move into Columbia Circle; the institution would remain in

[1] Thepaper.cn, "Preserving Old Shanghai: The Transformation of the Hundred-Year-Old Columbia Country Club," *Thepaper.cn*, March 11, 2021, accessed August 10, 2023, https://baijiahao.baidu.com/s?id=1693893002182819549&wfr=spider&for=pc.

[2] Wenjing Pan, Xuanxuan Xu, and Yawei Zhang, "Research on Historical and Cultural Inheritance and Renewal Strategy in Urban Renewal – A Case of Columbia Circle Renewal in Shanghai," *Urban Architecture* 17 (2020): 165.

[3] Ibid.

[4] Xinbao Su, "Urban Organic Renewal of Historic District – Columbia Park Project in Shanghai," *Contemporary Architecture* 6 (2018): 122.

[5] Ibid.

Columbia Circle until transferring to a site in the Fengxian district in 2016.[6] Some colonial-era structures of Columbia Circle, like the swimming pool of the Navy's Club, were incorporated into the institute as recreational facilities for employees. Most structures, however, were neglected.

Today, Columbia Circle is a revitalized neighborhood that pays homage to both eras of its history while simultaneously embracing new functions. Architects took a dynamic approach to the adaptive reuse of Columbia Circle—the historical integrity of crucial structures from the colonial era was ensured by restoration of the exterior and careful, non-obtrusive interior interventions. The thoughtful introduction of new space uses, like a bookstore in the Columbia Country Club and a restaurant in the Navy Club, ensured that these spaces did not fall into obsolescence and remained relevant components of the contemporary urban fabric. Structures from the Institute of Biological Products were evaluated based on their architectural value; some characteristics of the minimalist style of modern industrial heritage were kept, whereas unimportant structures were demolished and replaced with auxiliary buildings. The methodical and balanced approach is economically and socially appropriate to the adaptive reuse of Columbia Circle.

Most case studies of adaptive reuse sites discuss the transformation of functionality, allocation of financial assets, and application of technology to evaluate economic and environmental sustainability. There is limited social sustainability analysis, with most focusing on material metrics like investment, crime, and income.[7] However, the intangible cultural and social facet of adaptive reuse is equally as critical to heritage sites, especially those with complex histories. Theoretical discussions of the ethics and boundaries of adaptive reuse have always been divisive—while some claim that it is beyond our power to impose our interpretations on heritage, others believe that heritage must adapt to the times and our values. Is it justified to reinterpret architectural heritage to make it compatible with the values and demands of a modern context? If so, how is the balance between preservation and rehabilitation to be found? The case study of Columbia Circle sheds light on both questions. Adaptive reuse has made Columbia Circle not a relic of the past but a microcosm of Shanghai as an international and progressive city conscientious of its roots.

Columbia Circle's multifaceted heritage makes it a unique example of adaptive reuse. Most adaptive reuse sites are comprised of a dominant architectural style and hail from a distinct historical period. Xintiandi, one of Shanghai's earliest adaptive reuse projects, originated as a neighborhood of traditional Shikumen residential buildings dating back to the 1900s.[8] The adaptive reuse at the Royal Albert Docks in Liverpool centered around commercial and industrial heritage.[9] In these cases, the preeminence of a specific historical period gives the site a lucid identity. Columbia Circle has acquired a fair share of colonial and industrial identities over the past century. Its adaptive reuse cannot be interpreted simply through surface-level changes in appearance and function; changes in people's perception and interaction with the site are central to Columbia Circle's transformation. This paper explores Columbia Circle's adaptive reuse in the context of preservation theory and on-site fieldwork. The theoretical component of this study aims to lay out a framework for evaluating the ethics of

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[6] Ibid.

[7] Craig Langston et al., "Strategic assessment of building adaptive reuse opportunities in Hong Kong," *Building and Environment* 43 (2008): 1712.

[8] Xuefei Ren, "Forward to the Past: Historical Preservation in Globalizing Shanghai," *City and Community* 7 (2008): 9.

[9] "History," n.d., https://albertdock.com/history/.

Columbia Circle's reinterpretation of cultural heritage. As part of this component, perspectives on the value and treatment of historic architecture are presented and discussed. The writings of 19th-century theorists like Ruskin, Hardy, and Viollet-le-Duc are considered alongside contemporary charters from ICOMOS to provide a comprehensive survey of existing discourse, preservationist and restorationist, old and new. Ultimately, this paper combines arguments from various positions to analyze the appropriate approach to the complex and layered heritage at Columbia Circle.

Archival research and fieldwork were utilized to evaluate the social sustainability of Columbia Circle's structures and spatial layout. Archival resources provided the necessary historical background to assess whether restorative measures respected the historical integrity of the structures. Fieldwork was conducted to provide first-hand information on the social sustainability and cultural transformation of Columbia Circle. Observations focused on site-neighborhood relationships, user interactions, daily usage patterns, and overall atmosphere. Interviews with residents and visitors provided crucial testimonies. The results of the fieldwork are communicated through maps, photographs, original graphics, a table cataloging daily usage patterns, and interviews with locals and visitors.

The paper will introduce the discourse surrounding the preservation of architectural heritage. Recognizing that Columbia Circle is strongly associated with Shanghai's colonial era, an overview of Shanghai's colonial history and current attitudes to colonial heritage is provided. With the evaluative framework and background established, the case study of Columbia Circle is explored through the adaptive reuse of individual structures and the transformation of the spatial organization of the complex. Finally, the theoretical framework is used to justify Columbia Circle's adaptive reuse.

2. Theoretical Discussion

2.1. The Value of Architectural Heritage

This study draws attention to two central questions in the debate on the ethics and boundaries of adaptive reuse. Firstly, how should one judge the value of a historic building? Or, what attributes give a historic building value in being preserved or maintained? Secondly, all discussions of value aside, do architects have the right to alter and reinterpret historical heritage?

The precursor to the present debate on the conservation of architecture emerged in Victorian England. A fervent drive to restore medieval ecclesiastical architecture was sweeping across the nation; between 1840 and 1873, over 7,144 churches were restored, affecting almost all regions and communities. [10] Two distinct camps soon emerged: the restorationists, who supported rebuilding in the fashion of an anterior time, and the preservationists, who denounced restoration as a futile and destructive process. Fundamentally, they disagreed about the value of architectural heritage, specifically the role of history in shaping a building's identity.

The restorationist position regarded history as a traumatic process that

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[10] Benjamin Cannon, "The True Meaning of the Word Restoration: Architecture and Obsolescence in *Jude the Obscure*," *Victorian Studies* 56 (2014): 201.

could be reversed to attain an original state.[11] During the Victorian restoration debate, the Ecclesiologist Society Magazine was an influential proponent of the restorative approach. In a piece condemning church pews, which were viewed as a nefarious alteration to traditional Gothic architecture, editors championed "sweeping from our churches these records of a past and unhappy age."[12] This philosophy guided the Ecclesiologist Society to rebuild existing churches in the sanctified High Gothic style.[13] In other words, restorationists understood history as an accumulative process that needed to be remedied through violent decluttering and purification of the space; they saw the architect's role as expunging buildings of their corrupting additions to return them to some form of originality. In the case of Victorian England, the restorationists of the Ecclesiologist Society considered it compulsory to revise church buildings to fulfill what they saw as a ritualistic function.[14]

Like the English architects of the Ecclesiologist Society, the French architect Viollet-le-Duc was also formulating his theory of architectural restoration. To him, architecture was not a historical object confined by regionality and circumstance. He elevated the Gothic Cathedral into a romantic symbol and sought to emulate its unifying, singular essence in the buildings he renovated.[15] Restorationists like Viollet-le-Duc attributed the value of architecture to function and aesthetic form rather than the documentation of history. The present form of the building, having been morphed by the sinews of changing politics, culture, and communities, was not worth preserving per se.

Preservationists found it difficult to reconcile with this position. The first point of contention was the interpretation of history, as the preservationists saw history as irreversible and architecture as fundamentally altered by the events of history and physical wear. Thomas Hardy was among the most vocal advocates of the preservationist position. Hardy argued that far from being detached and dispensable, history was closely associated with architecture. The ill-conceived view of the relationship between history and heritage architecture espoused by restorationists was the culprit for "the damage done to this sentiment of association by replacement, by the rupture of continuity."[16] Hence, preservationists like Hardy portrayed history as a unidirectional and irrecoverable process.

The second point of contention concerned the value of heritage architecture itself. Hardy did not hold back in criticizing the restorationists for holding a utilitarian and materialistic position that demanded buildings "to be kept going, so that [they] may continue to discharge [their] original functions."[17] While restorationists were troubled with how to reanimate obsolete heritage architecture, Hardy and the preservationists relished the "deadness" and irretrievable original state of the building. Old buildings embodied a monumental quality deriving from their ability to inscribe the historical experiences of a people.[18] Instead of some ideal unifying quality, preservationists stress the unique ability of each building to

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[11] Ibid, 202.
[12] "Pues," *The Ecclesiologist* 2 (1842): 3–5.
[13] David Spurr, "Figures of Ruin and Restoration: Ruskin and Viollet-Le-Duc," in *Architecture and Modern Literature,* ed. David Spurr (Ann Arbor: University of Michigan Press, 2012), 152.
[14] Cannon, "Architecture and Obsolescence," 212.
[15] Spurr, "Figures of Ruin and Restoration," 153.
[16] Thomas Hardy, "Memories of Church Restoration," in *Thomas Hardy's Personal Writings*, ed. Harold Orel (Basingstoke: Macmillan, 1990), 215.
[17] Ibid, 204-05.
[18] Spurr, "Figures of Ruin and Restoration," 155.

narrate a story. As John Ruskin proclaims, "better the rudest work that tells a story or records a fact, than the richest without meaning."[19] It is no surprise that they attributed the value of architecture to history and association rather than function or form.

Although not an architect by profession, Ruskin is known for being among the most potent defenders of the preservationist position. He identifies architecture as a medium for memories:

> We may live without [architecture], and worship without [architecture], but we cannot remember without architecture [for it is the mighty representation] not only [of] what men have thought and felt, but what their hands have handled, and their strength wrought, and their eyes beheld, all the days of their life.[20]

Like a canvas, buildings offer themselves to the "golden stain of time"; they are not the work solely of the architect, but of all who have interacted with them.[21] No superfluous changes had to be extricated from the original work, as these alterations became an essential part of the building's identity.

Ruskin extends his argument from the human sphere to the natural sphere. He sees the physical wear and tear as imparting an accidental beauty to architecture, which he termed "sublimity."[22] The manifestation of age bestowed the "greatest glory" a building could hope to achieve. Unlike the restorationists, who portrayed history as a traumatic process to be reversed, preservationists regarded history as an invaluable process to be honored.

Therefore, it is unsurprising that Ruskin was highly critical of restoration. His stance is elucidated in the following passage from *The Seven Lamps of Architecture*:

> [Restoration] means the most total destruction which a building can suffer: a destruction out of which no remnants can be gathered... It is impossible, as impossible as to raise the dead, to restore anything that has ever been great or beautiful in architecture.[23]

Here lies the folly of restoration for Ruskin. It strives to isolate architecture from its history and context, notwithstanding the inextricable ties between architecture and the land it stands upon, the people who roamed its halls, and the elements that etched its walls.

Today, the value of architectural heritage is increasingly interpreted in the context of environmental sustainability. In the United States, the building industry is responsible for creating the greatest amount of CO_2 emissions.[24] Aside from the daily operations of a building, a significant amount of the CO_2 is embodied in the building itself: the acquisition, manufacture, transportation, and assemblage of building materials all translate into CO_2 emissions. Hence, it may take up to 50 years for even energy-efficient buildings to redress the CO_2 emitted during

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[19] John Ruskin, *The Lamp of Memory* (New York: John B. Alden, 1885), 8.
[20] Ibid, 3.
[21] Ibid, 11.
[22] Spurr, "Figures of Ruin and Restoration," 157.
[23] Ruskin, *The Lamp of Memory,* 18.
[24] Jean Carroon, *Sustainable Preservation – Greening Existing Buildings* (Hoboken: Wiley, 2010), 5.

construction.[25] This led restoration architect Carl Elefante to quip: "The greenest building is…one that is already built."[26] Historical buildings present a sizeable and often underutilized building stock that can be adapted to suit modern demands in a sustainable fashion.

2.2. The Treatment of Architectural Heritage

> No person within the town… shall unroof or dismantle any house without a decree of the senate, unless he shall intend to restore such house to its former condition.[27]

The above article belonged to *Lex Municipii Tarentini*, a set of laws governing the Roman Colony of Tarentum. This early piece of legislation demonstrates the great respect the Romans held for the Greek heritage they inherited and sketches out the parameters of how people were expected to treat architectural heritage. Despite being the product of a distant society, the principled and careful approach to architectural heritage *Lex Municipii Tarentini* delineates is a recurring theme throughout history.

Directed by their conceptions of architectural value coming from function and aesthetic form, restorationists generally took a more heavy-handed approach to architectural heritage. Viollet-le-Duc was rather distinctive in his treatment of architectural heritage, even when compared to fellow restorationists. By liberating architecture from its historicity and associations, Viollet-le-Duc asserted that any building exists in an ideal form that is distinct from the concrete form it occupies at any moment in history.[28] Hence, he did not attempt to re-create historic buildings in their original forms when he restored them; instead, he sought solutions to architectural problems the original architects may have encountered, adopting measures that he believed they would approve of had they had access to the technology of his day. In essence, Viollet-le-Duc was restoring from a priori principles—he worked with an idealized image of the historical building as embodying the unifying aesthetic qualities of its style.[29] He worked from a priori principles in his restoration of the Notre Dame Cathedral in Paris, altering the shape of the flying buttresses, changing the configuration of the walls, lowering the roof line, adding stained glass windows to the roundels, and sculptures to the angles and corners of the roof.[30] Paradoxically, in reclaiming history, Viollet-le-Duc goes against historical realities to attain the ideal form of architecture.

Preservationists opposed Viollet-le-Duc's daring reimagination of architectural heritage, advocating instead for maintaining the building in its present conditions. In the following passage from *Memories of Church Restoration*, Hardy explains:

> The protection of an ancient edifice against renewal in fresh materials is, in fact, even more of a social—I may say a humane—duty than an aesthetic one. It is the preservation of memories, history, fellowship, fraternities.[31]

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[25] Ibid, 8.
[26] "Insights," last modified 2023 https://carlelefante.com/.
[27] George Hardy Ernest, *Six Roman Laws* (Oxford: Clarendon Press, 1911), 108.
[28] Spurr, "Figures of Ruin and Restoration," 149.
[29] Ibid.
[30] Khaled Mohamed Dewidar, "Viollet Le Duc's Concept on Historic Preservation. The Egyptian Society of Political Science, Statistics and Legislation," *Transactions on the Built Environment* 26 (1997): 37.
[31] Hardy, "Memories of Church Restoration," 215.

Hardy saw preservation as a moral duty owed to the historical weight of architectural heritage; where Viollet-le-Duc saw an opportunity to interject his understandings of the ideal architectural form, Hardy saw "stones which had been stamped with the spirit from our ancestors." [32] Interestingly, while the preservationists emphasize the role of architecture as a medium for memory and witness of interactions, their position isolates old buildings from the activities of contemporary society, relegating them to the past.

The restoration debate continued to provoke discussions long after the times of its articulate Victorian orators. In post-WW2 Europe, people faced the difficult question of restoring historic buildings, neighborhoods, and even cities that perished during the turmoil. Now that the horrors of war had ingrained themselves in the historical experience of these buildings, was there any value in preservation? The history displayed by the ruinous rubble and fragmented remnants seemed a long shot from the "golden stains of time" that Ruskin suggested were worth preserving.

The significant damage inflicted made preservation untenable. However, instead of a purely restorationist approach of recreating the building's original form, adaptation was suggested as the appropriate way to honor the past. Basil Spence's Coventry cathedral preserved memories of wartime sacrifice in its tattered form, but its daring modern interventions demonstrated a forward-looking philosophy that refused to consign architecture to a specific era of history.[33] Across the war-torn continent, architects began rebuilding and restoring with the principle of adaptation instilled in their hearts, repurposing historical spaces to address the inevitable demand for new functions and spaces.[34]

Adaptation also comes up in discussions surrounding obsolescence. Defined as the sudden devaluation and expendability of architecture, obsolescence has been central to contemporary discourse on heritage value. Victorian preservationists were underpinned by fixed principles that honored the continuation of architecture as an embodiment of the past. This position became untenable as architecture became vulnerable not only to physical attrition but also to economic devaluation that tended to supersede structural life.[35] In his landmark work on obsolescence, Daniel Abramson suggests that obsolescence highlights the mortality and impermanence of architecture. Instead of treating the past reverentially like the preservationists, Abramson argues that obsolescence is best addressed through a flexible approach to the past that allows historical architecture to transform and adapt to the times.[36]

While a basic code of practice for architectural conservation had been established by the Athens Conference of 1931, the Venice Charter, drawn up in 1964, was the first significant milestone of the 20th-century conservation movement. The Charter affirms the importance of contributions from all time periods to historic monuments, recognizing the value of buildings as testimonies of historical changes. A stringent approach is adopted towards adaptive reuse, requiring architects to make their interventions clearly different from the original fabric. Restoration efforts should be substantiated by research and not rest solely

[32] John Ruskin, "The opening of the Crystal Palace," in *The Library Edition of the Works of John Ruskin,* ed. Alexander Wedderburn and E. T. Cooke (London: Allen, 1903), 432.

[33] Nicholas Bullock and Luc Verpoest, *Living with History, 1914-1964* (Leuven: Leuven University Press, 2011), 359-61.

[34] Ibid, 13-14.

[35] Daniel M. Abramson, *Obsolescence: An Architectural History* (Chicago: University of Chicago Press, 2016), 5.

[36] Ibid, 147.

on conjecture. Nonetheless, the Venice Charter calls for historic buildings to play a socially constructive role in modern society. Alterations of function to address modern demands are welcomed insofar as the general character and style of the buildings are preserved.[37]

Numerous other articles, standards, and guidelines followed the Venice Charter, expanding the scope of modern conservation work while providing indispensable benchmarks for practitioners. An important development of the Venice Charter came with the Burra Charter, which was conceived by the Australia International Council on Monuments and Sites (ICOMOS) in 1979. The Burra Charter introduced definitions for different forms of conservation: it defines restoration as "returning the existing fabric of a place to a known earlier state by removing accretions or by reassembling existing components without the introduction of new material," preservation as "maintaining the fabric of a place in its existing state and retarding deterioration," and adaptation (also referred to as rehabilitation) as "modifying a place to suit the existing use or a proposed use."[38] These definitions will be used when exploring adaptive reuse strategies at Columbia Circle.

Another crucial contribution of the Burra Charter is its flexibility in protecting varied heritage sites. While the Venice Charter was drafted with the distinctive architectural "monuments" of Europe in mind, the Burra Charter encompasses a broader assortment of sites, including vernacular buildings and indigenous communities. The Burra Charter's analytical framework considers five strands—aesthetic, historical, social, scientific, and spiritual—providing a more robust way to identify and assess heritage.[39]

The Burra Charter played an instrumental role in shaping analogous guidelines in China.[40] However, it is important to note that the traditions of restoration and preservation go far back in Chinese history; *The Analects* records Confucius commending kings for preserving temples built by their ancestors, as well as his verdict that the Treasure Chamber of Lu ought to be restored to its original form.[41]

The 21st-century requires a novel theoretical framework for evaluating and treating architectural heritage. 19th-century theorists like Ruskin, Hardy, and Viollet-le-Duc dealt with a limited scope of architectural genres. They focused on isolated buildings as targets of analysis. In the 20th-century, architects began to widen the scope of investigation to neighborhoods and cities, but discussions remained relatively limited. As new and complex forms of architectural heritage become the subject of adaptive reuse projects, we must consider how we approach networked sites with diverse and contradictory histories.

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[37] ICOMOS, "International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter 1964)," (Venice: ICOMOS, 1964).

[38] Australia ICOMOS, "The Burra Charter," (Melbourne: Australia ICOMOS, 2013).

[39] James Lesh, "Forty Years of the Burra Charter and Australia's Heritage Vision," *Foreground*, July 11, 2019, accessed January 25, 2024, https://www.foreground.com.au/culture/forty-years-of-the-burra-charter-and-australias-heritage-vision/.

[40] Z. Aygen, *International heritage and historic building conservation: Saving the world's past* (Milton Park: Taylor and Francis Group, 2012), 3.

[41] James Legge, *The Chinese Classics I: Confucian Analects* (Oxford: Oxford University Press, 1895).

3. Colonial Heritage in Shanghai

3.1. Shanghai's Colonial History

For nearly five centuries after its establishment in 1292, Shanghai was a market town of meager importance.[42] However, its geographical location at the mouth of the Yangtze on China's prosperous and densely populated east coast provided it with the prerequisites of becoming a major commercial center (Figure 4).

Figure 4. *Shanghai's location on the east coast of China places it in a prime location for trade and international commerce (source: Encyclopedia Britannica, 2023).*

Shanghai's rise to its status as an international city accompanied China's decline from a predominant world power. China's humiliating defeat in the First Opium War (1839-42) culminated in the Treaty of Nanking, which opened five Chinese ports, including Shanghai, to foreign merchants.[43] The Treaty gave foreign powers exclusive jurisdiction rights and special privileges; soon, the British, French, and Americans established enclaves known as concessions. Although the Chinese government had sovereignty over the concessions, they were administered independently at the discretion of the foreign governments.[44] In 1854, the three countries agreed to create the Shanghai Municipal Council (SMC) to coordinate their interests; while France dropped out of the arrangement in 1862, the SMC was retained as the administrative authority for the International Settlement that formed when the British and American settlements were combined in 1863.[45]

Alarmed by the unrest sparked by the Taiping rebellion, the SMC began constructing extra-settlement roads in the 1860s to connect concessions to critical foreign-protected assets in Chinese-administered territory.[46] The SMC was granted administrative rights over areas adjacent to these extra-settlement roads, creating a series of "quasi-concessions." For the next few decades, the SMC would use extra-settlement roads as a pretext to expand the International Settlement further west and north. The Columbia Country Club and the surrounding

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[42] Lena Scheen, *History of Shanghai* (Oxford: Oxford University Press, 2022).
[43] "History of Shanghai," last modified August 22, 2023, https://www.britannica.com/place/Shanghai/History.
[44] Qian Guan, *Lilong Housing, a Traditional Settlement Form* (Montreal: McGill University School of Architecture, 1996), 12.
[45] Ibid, 13.
[46] "Shanghai International Settlement," n.d., https://academic-accelerator.com/encyclopedia/shanghai-international-settlement.

neighborhood of Columbia Circle originated as quasi-concessions along extra-settlement roads (Figure 5).

Dubbed the Paris of the East, Shanghai's status as an international metropolis reached its zenith in the 1920s and 1930s; the glamorous dance halls, imposing financial headquarters, and foreign-run racetrack indicated it was a city catering to the lifestyle of high society. Yet beneath its extravagant appearance was the cheap labor of hundreds of thousands of poverty-stricken Chinese.[47]
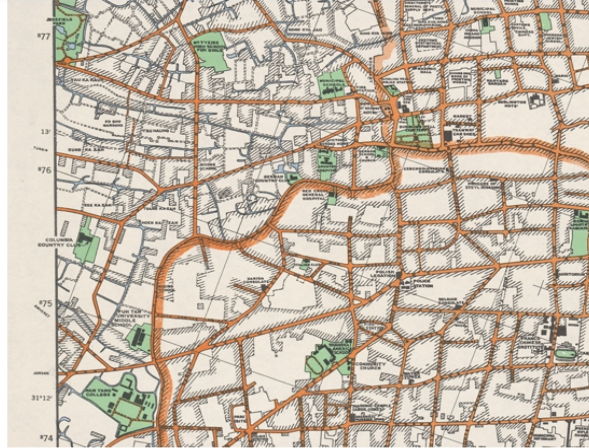
Figure 5. *A map extract showing Shanghai's western districts in 1933. The settlement boundary is demarcated with the thick orange line. Note the location of the Columbia Country Club on the far left of the map extract beyond the settlement boundaries beside extra-settlement roads (source: image by Shanghai Municipal Council, 1933, and reproduced by the US Army, 1945 http://www.lib.utexas.edu/maps/ams/china_city_plans/txu-oclc-6567312-1.jpg).*

3.2. Attitudes to Colonial Heritage in Shanghai

Shanghai's colonial era left a controversial legacy. When the People's Republic of China (PRC) was established in 1949, communist authorities immediately began a campaign to rid Shanghai of its colonial heritage. The racecourse, a recreational facility for foreigners and wealthy Chinese, was interpreted as a symbol of privilege and colonial inequality. Chen Yi, the first communist mayor of Shanghai, had the racecourse demolished and replaced by People's Park.[48] The accompanying Clubhouse was transformed into the Shanghai Library and Shanghai Museum, designated as public educational institutions.[49] Authorities used the anti-colonial

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[47] Kristin Baird Rattini, "A Short History of Shanghai," *The New York Times*, n.d., accessed August 20, 2023, https://archive.nytimes.com/www.nytimes.com/fodors/top/features/travel/destinations/asia/china/shanghai/fdrs_feat_145_5.html?n=Top%252FFeatures%252FTravel%252FDestinations%252FAsia%252FChina%252FShanghai.

[48] Jan Ifversen and Laura Pozzi, "European Colonial Heritage in Shanghai: Conflicting Practices," *Heritage & Society* 13 (2020): 146.

[49] Ibid.

drive to demonstrate their commitment to reclaim exclusive spaces for the benefit of the populace.

The hostile approach to colonial heritage subsided after the reforms of the late 1970s. For many years, colonial heritage in Shanghai fell into a state of neglect. By the 1990s and early 2000s, there was a rise in "Shanghai nostalgia," a reminiscence of Shanghai's colonial past tinted by romantic images of luxury.[50] This nostalgia was primarily found in Shanghai's "upper quarters", neighborhoods that foreigners had formerly inhabited.[51] The rose-tinted reimaginations of the colonial era prompted a wave of consumerism associated with colonial heritage; real estate developers seized this opportunity to redevelop Shanghai's colonial heritage in high-profile cases like Xintiandi and the Sinan Mansions.[52]

In recent years, colonial heritage has found a new place in the social and political agenda of the Shanghai government. Authorities reframed colonial heritage by disconnecting sites from their colonial past and emphasizing their architectural qualities to indicate a diversity of styles.[53] Elsewhere, colonial sites became symbols of China's cultural exchanges with other countries, fulfilling the objective of rebranding Shanghai as an inclusive global city, the bridge between China and the world.[54]

4. Reinterpreting Columbia Circle's Colonial Heritage: Balancing Preservation and Rehabilitation

4.1. The General Approach to Adaptive Reuse

In Columbia Circle, adaptive reuse balances the preservation of the historic identity of structures with modern demands to ensure social and economic viability. Two distinct approaches were taken, depending on the protection status of the structure.

All three of Columbia Circle's protected structures belong to the colonial era—the Columbia Country Club, the Navy Club and its swimming pool, and Sun Ke Villa—and were retained during adaptive reuse.[55] A conscientious approach was taken to restore the exterior of the structures to reflect accurately their appearance when they were first constructed. Most structural additions and renovations made to the protected structures during the SIBP era were removed; where historic features were missing or incomplete, architects restored them because the changes would be reversible and identifiable from the rest of the structure. In most cases, interior décor was also restored to its original state, unless SIBP additions were deemed to contribute to the narrative and identity of the structure. Compared to the exterior, architects had more freedom to introduce modern interventions inside structures to create opportunities for new uses; nonetheless, they were still requested to minimize the extent of intervention and

50 Tianshu Pan, "Historical Memory, Community-Building, and Place-Making in Neighborhood Shanghai," in *Restructuring the Chinese City*, ed. Laurence J.C. Ma and Fulong Wu (London: Routledge, 2004), 110.
51 Ibid, 111.
52 Ran Wei and Fang Wang, "Is Colonial Heritage Negative or not so Much? Debating Heritage Discourses and Selective Interpretation of Kulangsu, China," *Built Heritage* 6 (2022): 4.
53 Ifversen and Pozzi, "Conflicting Practices," 153.
54 Wei and Wang, "Debating Heritage Discourses," 4.
55 Su, "Urban Organic Renewal," 122.

ensure that the original structure was not damaged.[56] This conveyed a sense of respect for the historical integrity of the site and a clear distinction between the old and the new.

The industrial buildings constructed during SIBP's tenure were not classified as protected sites and demanded a different strategy. Architect Su Xinbao succinctly described the guiding approach to these structures as one of "maintain, adapt, demolish."[57] The constantly growing production requirements of SIBP led to the construction of over 40 structures, most with limited architectural value due to the emphasis on practicality and the absence of a coherent expansion plan.[58] After demolishing haphazard structures, 12 remaining buildings were kept to undergo adaptive reuse. The closed façades of these structures were inconducive to consumer interaction and the presentation of products. Hence, it was necessary to alter them significantly to attract businesses. Most structures in the "adapt" category were built during the 80s with a highly functional purpose and a lack of stylistic characteristics.

This was not to say that all industrial buildings were considered worthless. Some, like the MMR production building opposite the Columbia Country Club, were exemplary reflections of modernism and had their overall appearance maintained. Furthermore, architects recognized the extraordinary contribution these more contemporary buildings made to the overall diversity of Columbia Circle. Wu Lei, an East China Architectural Design Institute (ECADI) architect who participated in the adaptive reuse, expressed the team's desire to celebrate the distinct stories embodied by each building; they avoided the common practice of unifying seemingly disparate structures under a singular style, opting for an approach that respected the unique individuality of each structure.[59]

The industrial structures were also seen as harboring an irreplaceable sentimental value. Despite the solitary nature of SIBP's work, many local residents had developed a sentimental connection with SIBP, due either to work or to the seemingly interminable presence of the plant's looming structures over the predominantly residential neighborhood. The emotional value of SIBP's structures needed to be cultivated for the adaptive reuse to qualify as socially sustainable.[60] Although Elliott Hazzard and the colonial era opened the first chapter of Columbia Circle's history, it was SIBP and the industrial era that narrated its longest chapter. Industrial heritage had become inseparable from Columbia Circle's identity and public perception.

4.2. The Columbia Country Club

Located centrally within the complex, the Country Club is easily the focal point of the diverse individual structures of Columbia Circle. The Country Club had a rich historical heritage that warranted protection; it was the most historic structure on site and was aesthetically representative of the architectural styles that defined Shanghai's colonial era. In 1999, the Country Club was designated as a protected site with municipal supervision. By then, the building had become the administrative office of SIBP, and the vicissitudes of history had left its key

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[56] Ibid, 123.
[57] Ibid.
[58] Ibid.
[59] Lei Wu, "Inclusivity and Diversity in Urban Renewal—the Case of Columbia Circle," *China Engineering and Consulting* (2020): 52.
[60] Xiangli Jing and Jingquan Wan, "Escaping from the 'Industry Park' Model in Urban Renewal— the Case of Columbia Circle," *China Real Estate* 23 (2020): 22.

architectural features in a state of disrepair. [61] As part of the adaptive reuse strategy, architects adopted a balanced approach of restoration and rehabilitation to emphasize the external characteristics of the building while opening the interior to modern interventions.

Elliott Hazzard fashioned the Country Club in the Spanish Mission Revival Style, common in his native region of Southern California. A handsome two-story structure with a total interior area of 2012 square meters and a main south-facing façade spanning 52 meters, the Country Club has a commanding presence and an unparalleled aesthetic value among the other structures in the complex. [62] The north façade of the building has a porte-cochere embellished with curvilinear parapets, a lion finial, and two pairs of spiral columns (Figure 6). These spiral columns, a hallmark of the Spanish Mission Revival Style, are of the Roman composite order, combining the volutes of the Ionic order with the acanthus leaves and floral elements of the Corinthian order (Figure 7).

Prior to adaptive reuse, the column bases were no longer visible, as the ground level had been raised significantly over the years as SIBP re-paved the roads within the complex multiple times. Architects decided to lower the ground level of the entire north façade to expose the base of the columns (Figure 7). [63] This reflected the approach to architectural heritage at Columbia Circle—returning architecture to its original appearance through recreating and restoring distinctive stylistic details. Individual structures like the Country Club can stand out as being anchored to a specific era and emanate an enduring sense of place and time by virtue of this approach.

Figure 6. *The porte-cochere, which is now the main entrance to Tsutaya Books; note the lion finial and low parapet, both distinctive features of the Country Club building. Photo by author.*

Figure 7. *Spiral columns in the porte-cochere with their bases restored; notice how the ground level was lowered to achieve this. Photo by author.*

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[61] Pan, Xu, and Zhang, "Renewal Strategy," 165.

[62] Yun Wang, "Restoration of Historical Buildings in Shanghai—The Columbia Country Club," *China Residential Facilities* (2020): 23-25.

[63] Thepaper.cn, "Preserving Old Shanghai."

The south façade was restored to its original appearance in a similar manner (Figure 8 and Figure 9). Recreating the stucco, which had been severely impacted by weathering the accumulation of dust and pollutants, was an emphasis of the restoration effort. [64] Elsewhere, the distinguishing features of Spanish Mission Revival architecture—the red-tiled roof, clay-tiled roof vents, round arch windows, and intricately carved wooden multi-paned windows—were all intact (Figure 10). [65] For these features, the effort was centered on cleaning and repairing broken components to their original appearance.

Figure 8. *Archival footage of the south façade of the Columbia Country Club in the 1920s (source: Thepaper.cn, 2021).*

Figure 9. *The Columbia Country Club's south façade after adaptive reuse; the south façade has been largely restored to its appearance upon completion in 1924, with the exception of the awning above the arcade. Photo by author.*

Entering the interior of the building, a colonnade stretches horizontally between the main body of the Country Club and the north façade. The spiral columns in the porte-cochere are repeated in the interior, creating an essential motif for the Country Club. The main room on the first floor is an expansive space with exposed wooden beams on the ceiling supported by rows of columns. Again, the restoration of characteristic features like the ceiling cornices and wooden wainscoting was prioritized; the spiral columns and stone fireplaces on the east and west walls were in relatively good condition and retained. [66]

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[64] Wang, "The Columbia Country Club," 24.
[65] Chris Jennewein, "Weekend Design: All about California's Spanish Eclectic Style," *Times of San Diego*, November 6, 2016, accessed August 12, 2023, https://timesofsandiego.com/life/2016/11/05/weekend-design-all-about-californias-spanish-eclectic-style/.
[66] Wang, "The Columbia Country Club," 23.

Figure 10. *Collage by author of the Columbia Country Club after adaptive reuse. Note the distinct Spanish Mission Revival features that were restored during adaptive reuse, including the round arch windows, curvilinear gables, and stucco walls.*

During the adaptive reuse that transformed the Country Club into Tsutaya Books, the basic spatial layout of the interior was maintained. The spacious column layout gave developers the freedom and convenience to reorganize the space with modern interventions; Tsutaya Books used a series of free-standing metal frames fitted with lighting to brighten the space, minimizing the impact rehabilitation had on the structural components of the ceiling.

There was a conscious effort to encourage the new to interact with the old. As the centerpiece of Columbia Circle, the Country Club acquired the role of educating visitors not only on the site's history, but also on Shanghai's contemporary history. Short descriptions of bygone eras coupled with historical maps and images can be found on large transparent glass panels among the bookshelves (Figure 11). Spiral columns cast their sinuous forms through the glass, organically blending with the modern additions in a cohesive space. Walking past, the visitor's eyes are drawn upwards to the ornate capitals illuminated by the soft glow of lights below. By combining a respect for the historical truthfulness of restoration and a pragmatic yet non-obtrusive attitude towards rehabilitation, architects were able to sustainably adapt the Country Club for posterity.

Figure 11. *Glass panels printed with descriptions of Columbia Circle's history. In the background, metal frames supporting lighting features and shelves act as minimally disruptive modern interventions to the historical space. Photo by author.*

4.3. The Navy Club

Built to complement the main structure of the Columbia Country Club, the Navy Club accommodated the sports recreational facilities for the expatriate community. Being the work of Elliott Hazzard, the Navy Club also incorporated notable features of the Spanish Mission Revival in its architecture, with distinctive curvilinear north-facing gables, elegant arched windows, and rose-patterned vents. During the colonial era, it had an indoor gym, a bowling alley, and an open-air swimming pool surrounded by a one-story colonnade.

The Navy Club differed from the Columbia Country Club in that SIBP made significant alterations to the layout and structure of the buildings. After SIBP took over the site, the gym was repurposed into the steamer room for cultivating biological cultures. Large machines were added against the walls, along with dust-removing chutes and vents. The color palette of the interior was also transformed as the walls were repainted in a light green tone. In comparison, the swimming pool retained its original function and became an exclusive facility for SIBP employees. It was also during this time that a second level was added to the poolside colonnade (Figure 12).[67]

Instead of restoring the Navy Club to its original state in the colonial era, architects tried to thread the legacy of the SIBP into adaptive reuse. The heavy machinery was removed, but the green color palette and dust chutes were retained as a reminder of the building's former industrial identity. Where modern appliances were added to meet cooling requirements, architects tried to make the interventions unnoticeable; the air conditioning vents used the rose-patterned vents of the original structure.[68] Nor did architects restore the poolside colonnade to its original appearance; the second level added by SIBP was preserved and converted into prime retail and dining space overlooking the pool.

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[67] Pan, Xu, and Zhang, "Renewal Strategy," 165.
[68] Ibid.
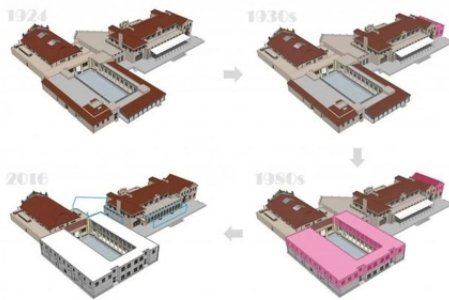
Figure 12. *Changes in the poolside colonnade of the Navy Club over time. The addition of the second level in the 1980s increased density and altered the original structure of the colonnade. Architects retained the second level during adaptive reuse as it created space for poolside businesses (source: Thepaper.cn, 2021).*

Notably, the swimming pool is no longer a sports venue but a tourist attraction. Western fine dining options and bars use the colonnade as space for outdoor seating (Figure 13). The photogenic azure pool water and skillful mosaic work have made the Navy Club swimming pool a popular location on Chinese social media platforms like Xiaohongshu. The cultivation of internet-celebrity status has been a crucial goal for many Chinese developers, as the pervasive social media influence among young people raises the profile of sites and draws visitors.[69] The Navy Club swimming pool fills this role for Columbia Circle.

Figure 13. *A corner of the Navy Club swimming pool. A stark color difference exists between the original colonnade and the colonnade added on the second level during the SIBP era. The colonnades have been transformed into an outdoor dining space. Photo by author.*

4.4. Industrial Heritage and Modern Interventions

Aside from the Columbia Country Club, Navy Club, and Sun Ke Villa, the remaining structures in Columbia Circle are either repurposed industrial structures or newly built structures. Different approaches were taken regarding industrial heritage depending on the building's historical value, aesthetic value, and adaptability. Modern interventions were made to introduce variation and liven up the industrial fabric.

The most notable industrial building preserved on site is the MMR building, built in 1965 to house the MMR vaccine's research, design, and production facilities (Figure 14). Upon completion, the ten-story MMR building was the tallest structure in the Changning district.[70] Its chief architect, Guo Bo,

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[69] Yueyang Ma and Haitao Jiang, "Practical transformation of critical regionalism in internet-era China—viral architecture," *Chinese and Foreign Architecture* 9 (2021): 118-121.
[70] Pan, Xu, and Zhang, "Renewal Strategy," 166.

drew heavily on the simplicity and geometricity of the Bauhaus movement.[71] Dividers split the north façade into slim columns lined with identical rectangular windows on each level, creating a strong sense of verticality. The white walls are devoid of ornamentation—this was the emblem of functionalist architecture. The decision to maintain the MMR building stemmed from two considerations: firstly, its historical significance as an important scientific venue symbolic of China's progress in biomedical engineering; secondly, its aesthetic value as a reflection of modernism in architecture that adds diversity to Columbia Circle. Therefore, aside from refurbishing the exterior paint layer and replacing the windows, very little intervention was taken during adaptive reuse, and the MMR building retained its function as an office space.

Figure 14. *The refurbished MMR building looking out over the main square. To the right, the structure covered in mirror stainless steel is the former appliance building for the MMR building and has since been significantly altered to add dynamism to the main square (source: Thepaper.cn, 2021).*

An entirely different approach was taken for the subsidiary appliance building on the northwestern corner of the MMR building. Despite being built along with the MMR building in 1965, architects determined that the subsidiary building did not possess value in being preserved; its façade was mundane and lacked windows, antagonistic to the open and vibrant atmosphere envisioned for the main square.[72] Hence, the building was rebuilt with a striking façade made of mirrored stainless steel that captured the reflection of the prominent structures populating the main square—the Columbia Country Club and the MMR building (Figure 14). This design symbolically promotes the cohesion of the site's disparate histories, one colonial and one industrial, and allows the building to blend in with its surroundings. The mirrored façade also creates an impression of spaciousness.

Elsewhere, a balanced strategy of preservation and rehabilitation was adopted. The former procurement building, built in 1984, overlooks the entrance square of Columbia Circle. Its prominent location made it a focus of the adaptive reuse effort for Columbia Circle's industrial heritage. Critical components of the building's industrial identity were retained, including the wrought iron gate on the first floor and cast-iron windows.[73] Nonetheless, considering that the building was to be repurposed for commercial and retail use, the windows on the second floor were expanded to allow more light into the interior, and a braced cantilevered

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[71] Rex Provost, "Bauhaus—Art Movement, Style & History Explained," *StudioBinder*, last modified September 4, 2022, https://www.studiobinder.com/blog/what-is-bauhaus-art-movement/#:~:text=The%20Bauhaus%20is%20a%20German.

[72] Wu, "Inclusivity and Diversity," 55.

[73] Ibid.

balcony was introduced on the same floor to offer outdoor space for retailers and inject dynamism into the plain functionalist façade. The adaptive reuse of the procurement building embodies the thoughtful attitude taken towards heritage architecture. A careful evaluation of characteristic elements ensures that history is preserved and represented; at the same time, the daring infusion of modern construction prepares the building for new life and service for its occupants.

4.5. Building a Sense of Place Through Businesses

Columbia Circle was revitalized economically as the rehabilitation of structures created opportunities for businesses to move in and support the site in cultivating a new profile and sense of place. There is an emphasis on developing Columbia Circle into a gathering place for cultural and art enthusiasts (Figure 15). Most of Columbia Circle's office space is rented to businesses in the creative cultural sector, and many shops sell cultural products. The former procurement building currently houses two culture-related franchises of ZucZug, a Shanghai-based female fashion brand, Klee Klee and Friends and Naze Naze, both specializing in textiles and fabrics inspired by ethnic art in Southwestern China. These small-scale designer workshops with an important social mission fit perfectly into the business environment of Columbia Circle; the youthful and culturally conscious profile of Columbia Circle visitors makes them especially receptive to and supportive of such avant-garde initiatives. The balance between cultural production and cultural consumption makes Columbia Circle a prominent cultural hub with the entire chain from design to consumption.[74]
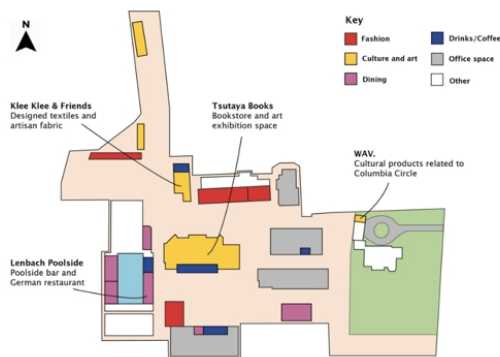
Figure 15. *Map by author showing the location and types of businesses found at Columbia Circle. Four prominent and representative businesses are marked.*

Tsutaya Books, the largest bookstore chain in Japan, opened its first Shanghai store in the Columbia Country Club in 2020.[75] Spanning two floors, Tsutaya Books hosts an extensive collection of Chinese and English books, focusing on art books and cultural products. The relationship between Columbia Circle and Tsutaya Books is mutual; while the historical background and aesthetic

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[74] Jiemei Luo et al., "The social value and activities of urban cultural heritage spaces—Columbia Circle and Tai Kwun," *China Urban Planning Conference* (2021).

[75] Yuming Ren et al., "[in Photos] Japan's Tsutaya Books Opens First Shanghai Store," *Yicai Global*,
December 25, 2020, accessed August 15, 2023, https://www.yicaiglobal.com/news/in-photos-japan-tsutaya-books-opens-first-shanghai-store-.

architecture of the Country Club complement the atmosphere of the bookstore, the bookstore contributes to the promotion of Columbia Circle's cultural scene by hosting public art exhibitions and making itself an integral part of the public perception of activities at Columbia Circle.

WAV., the official Columbia Circle merchandise store, is adjacent to Sun Ke Villa. As a subsidiary company of the site developer, Vanke, WAV. focuses on marketing cultural memorabilia and artisan items related to Columbia Circle; scarves, mugs, and trinkets are printed with depictions of the Navy Club pool, the Columbia Country Club, and Sun Ke Villa. WAV. romanticizes the colonial past of Columbia Circle by portraying the fashion and style of the 1920s and 1930s in an elegant and whimsical light; there is no mention of the exclusivity and historical background of Shanghai's colonial era. In comparison, the industrial heritage of SIBP is left untouched by WAV.'s designs. Tasked with building a public image for Columbia Circle, WAV.'s decisions of what to include in its designs and how those elements are depicted suggest how developers want Columbia Circle to be viewed. WAV.'s bias in developing products associated with the colonial past of Columbia Circle generates an unmistakable cosmopolitan identity.

The repackaging of Shanghai's colonial era is taken a step further at the Navy Club pool. Here, several bars and restaurants serving Western cuisine and drinks can be found clustered around the pool behind the colonnade: the Lenbach Poolside serves German meals, and Casa Baja serves Spanish tapas. Aside from a high-end restaurant located off the main square, traditional Chinese-styled cuisine is limited. The variety of Western dining establishments represents a Shanghainese take on the themes of internationalism and cultural fusion—Columbia Circle brands itself as the dialogue between the domestic and foreign, just as it facilitates a similar interaction between the colonial, industrial, and contemporary elements of its architecture (Figure 16).

Figure 16. *Collage by author of some businesses at Columbia Circle. Most businesses target a youthful audience interested in arts and culture; there is also a significant presence of Western cuisine and fashion that takes advantage of Columbia Circle's cosmopolitan colonial heritage.*

5. Reinterpreting Columbia Circle's Colonial Heritage: Shaping a New Identity

5.1. The Relationship Between Columbia Circle and its Neighborhood

For most of its history, Columbia Circle was associated with exclusivity. Conceived in the colonial era, Columbia Circle was the stomping ground of elite American expatriates residing in Shanghai's concessions. The exclusivity of the site was exacerbated by the fact that it lay beyond the boundaries of the concessions but remained off-limits to local Chinese residents.[76] Nor was it solely a reflection of the divide between the foreign and domestic communities; it also highlighted the stratification of social classes. These factors combined to give Columbia Circle an impenetrable air of extravagance.

The elitist connotations of Columbia Circle ceased to exist after SIBP took over the complex in 1953. However, its impenetrable impression remained. Looming towers like the MMR building and vast factory halls with very few external openings stood between the neighborhood and the rest of the complex; except for one sentry-guarded entrance on West Yan'an Road, all other entrances to the complex were sealed off. SIBP would operate in this closed and strictly managed environment for the next 63 years. Residents recall that SIBP appeared disconnected from the neighborhood, despite its dominating presence:

> It definitely seemed like somewhere we weren't supposed to go. They were doing scientific research and production in the complex, so naturally everything was heavily scrutinized. You couldn't see the interior of the complex from the streets because large buildings blocked the view.[77]

During the SIBP era, the main entrance lay on West Yan'an Road, a major car-centered transportation artery with an elevated urban highway running above. This suited the transportation demands of the industrial complex, but limited pedestrian access. The central divider, width, and significant traffic flow of West Yan'an Road discouraged residents living north of the road from crossing. Residents on the south side had to make a considerable detour to access the site.

Figure 17. *Map showing the relationship between Columbia Circle and its neighborhood (source: modified figure by author based on image from Google Earth, 2023). During the SIBP era, access to the site was extremely limited, as only the north entrance on West Yan'an Road was open.*

76 Thepaper.cn, "Preserving Old Shanghai."
77 S. Pan (retired teacher) in discussion with the author, August 7, 2023.

Reintegrating urban industrial heritage into the urban landscape requires an inclusive effort considering local socio-economic conditions.[78] Planners tackled the physical divide between Columbia Circle and the surrounding Xinhua Road neighborhood by establishing three additional access points to the complex (Figure 17). The original main entrance on West Yan'an Road was retained to serve visitors accessing the site via taxi or metro, but efforts were made to redefine Columbia Circle as a public space for the neighborhood. An entrance was opened on Anxi Road for convenient access from the west side, where residential apartment compounds provide a large potential user population for Columbia Circle. A smaller entrance passage was built on the east side, connecting to a quiet residential area on Panyu Road (Figure 18). An exit on the south side is planned to open along with phase two of Columbia Circle's redevelopment.

Figure 18. *Photo by author showing the entrance on Panyu Road that leads to a quiet residential area.*

The strengthened physical connection between Columbia Circle and its local community embeds the complex firmly in the neighborhood fabric; this sets the foundations for an open and inclusive perception of the site. The social sustainability of Columbia Circle rests on its successful transition from a closed to an open space. The newfound vitality and popularity of Columbia Circle fosters local pride by elevating the neighborhood's image. By establishing itself as an accessible meeting place receptive to people of all ages, income levels, and occupations, Columbia Circle becomes a relatable and identifiable location for the community. Moreover, Columbia Circle plays an integral role in the daily routine of many residents, providing a platform for people to meet and interact with other members of their community. The promotion of a strong social life for locals creates a sense of belonging in the community that improves wellbeing.[79]

5.2. Local and Visitor Interactions with Columbia Circle

Both locals and visitors use the Anxi Road entrance leading to the entrance square. Locals reaching Columbia Circle by foot may also use the Panyu Road entrance.

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[78] Stefania Gregoria et al., "Designing the Sustainable Adaptive Reuse of Industrial Heritage to Enhance the Local Context," *Sustainability* 12, no. 21: 9059.

[79] Nicola Bacon, Douglas Cochrane, and Saffron Woodcraft, *Creating Strong Communities: How to Measure the Social Sustainability of New Housing Development* (London: Berkeley Group, 2012).

Visitors, by comparison, prefer the West Yan'an Road entrance due to its good connection to external transportation options. As a result, locals usually move through the site along an east-west axis, whereas visitors tend to concentrate in the northwestern and central parts of the complex.

Within the complex, locals and visitors engage in different activities. Visitors are usually motivated by social media and aim to reach all the photogenic locations within the constraints of their schedule. They often set out to explore the historic structures on site, concentrating on the Navy Club pool and Tsutaya Books in the Columbia Country Club building. Some make an effort to visit Sun Ke Villa, but as the Villa entails an entrance fee, it is less frequented. Cultural shops and businesses also tend to attract visitors due to their niche focus and boutique atmosphere. Locals, being accustomed to the complex, incorporate Columbia Circle into their daily routine and experience the site more leisurely. They choose to spend time in local coffee shops and restaurants.

The two paths converge in the public spaces of Columbia Circle. The entrance square, main square, and various public seating areas provide the setting for interactions between locals and visitors in Columbia Circle. For locals and visitors, these areas facilitate playing, resting, and relaxation and naturally become hubs of activity (Figure 19).
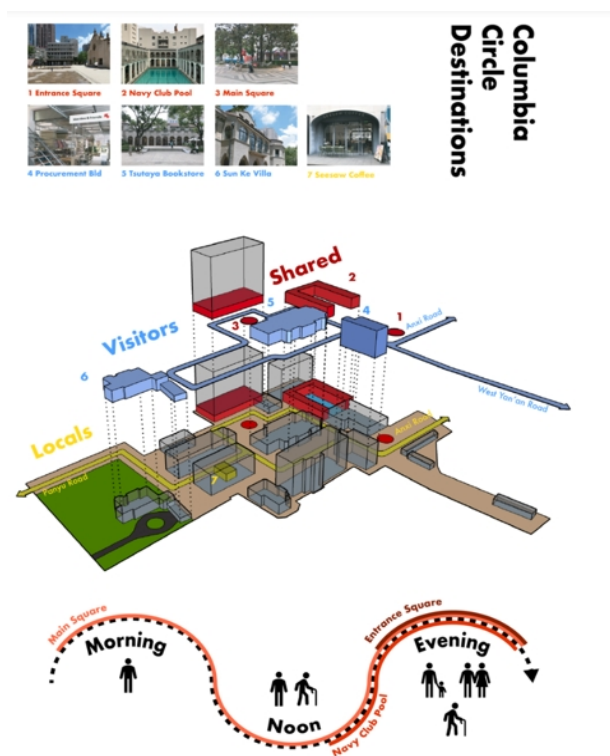
Figure 19. *Graphic by author showing destinations and paths for locals and visitors, as well as a timeline illustrating when shared spaces are used and by whom.*

5.3. Public Spaces at Columbia Circle

Once the physical divide had been bridged through improved outward connections, bridging the cultural and social divide was necessary. The dynamic and multi-faceted public spaces incorporated into Columbia Circle during adaptive reuse are the site's main drivers of social and cultural sustainability. The public squares between buildings offer a means of transition between juxtaposed structures and play an indispensable role in creating an inclusive character for Columbia Circle. As part of the fieldwork, I observed the activities taking place at various locations around Columbia Circle during a weekday in the summer, from 8:00 in the morning to 6:00 in the evening. Specific attention was paid to the number of people, the distribution of people, and the attributes (age, in groups. or alone) of visitors and locals. A variety of activities involving people of all ages and backgrounds takes place across the shared spaces of Columbia Circle daily. It can be summarized in the following table from the fieldwork showing usage patterns during the summer (Table 1).

Table 1. *Usage patterns in Columbia Circle throughout the day during summer*

Time	Hotspots	Activities	People
Morning	Main square, seating areas	People resting in the main square	Visitors
Afternoon	Main square, seating areas	Children playing in the main square; people resting	Visitors, elderly, families with young children
Evening	Entrance square, main square	Children playing in the fountain	Families with young children, couples, friends

The main square is the center of activity for most hours of the day. Located between the Columbia Country Club building and the MMR building, it is frequented by locals and visitors alike. The shaded seating areas under trees and benches along buildings encourage people to rest and utilize the public space; art installations give the square a distinct sense of place and identity. Here, the public space is no longer simply a backdrop to historic buildings; it is an essential part of Columbia Circle, contributing to the identity of the complex in its own right, subverting the architectural theorists' traditional emphasis on individual structures. Indeed, most overlapping hotspots on the local and visitor paths through Columbia Circle are public spaces rather than specific buildings. The reimagining of Columbia Circle shifts the gravity of the site from the weight of its historical heritage to the negative spaces in between that promote collective discourse, interaction, and activity.

When visiting on a late afternoon during the summer, I witnessed the different ways people interpreted this public space. Some children played tag as their parents and grandparents watched on from the shaded seating area, casually chatting with each other. People were reading books, scrolling through messages on their phones, or staring into space in a moment of self-meditation (Figure 20). Some were interacting with a piece of interactive art inspired by the works of Alice Melloni, an Italian artist based in Shanghai.[80] As part of Columbia Circle's public

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[80] Yuting Zhu, "Shanghai Inspires Changes in How Italian Woman Makes Her Art," *SHINE*, February 28, 2022, accessed August 16, 2023, https://www.shine.cn/news/metro/2202282475/.

art initiative "Be Inspired," organizers installed two-meter-tall sculptures of flowers that would open if someone waved at the flower bud. The motion input of the user directly influences the dynamic form of the artwork, allowing the public to engage and participate in the artwork (Figure 21). [81] By facilitating these interactions, Columbia Circle can redefine itself as an inclusive, receptive, and non-discriminatory environment where everyone can experience art. This is an important strategy of the adaptive reuse process that tries to remove the elitism associated with colonial heritage so the complex can be better integrated into the community.

As night falls, the action shifts to the entrance square. The primary draw of the entrance square is its rows of ground fountains that activate in the late afternoon. Unlike the main square, the entrance square is not shaded by trees, so activities only take place during the cooler temperatures of the night (Figure 22). Its location close to two main access points—the Anxi Road entrance and West Yan'an Road entrance—makes it a convenient after-dinner stop for locals, especially those with young children. As a mother of two explains:

> We live around a five-minute walk from here. During the summer, we come here nearly every night after dinner so the kids can play in the fountain. It's a great place for them to be active and meet new friends. [82]

Hence, the dynamic activities available in Columbia Circle's public spaces provide ideal spaces for fostering a sense of community. This exemplifies Columbia Circle's transformation from a barricaded and unapproachable neighborhood giant during the SIBP era to its proactive role after adaptive reuse as a landmark that brings cohesion to the neighborhood.

Figure 20. *People resting in the shaded public seating areas of the main square; note the variety of art installations that provide unique interactive experiences to the public. These features make the space interesting and vibrant. Photo by author.*

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[81] Jun Hu et al., "Designing interactive public art installations: new material therefore new challenges," *Lecture notes in computer science* 8770 (2014): 200.
[82] J. Liu (mother of two) in discussion with the author, August 7, 2023.

Figure 21. *Children sitting under an interactive art installation at the main square in the late afternoon. Photo by author.*

Figure 22. *Families enjoying the early evening at the entrance square fountains. The entrance square becomes very popular starting from the early evening. Photo by author.*

6. Evaluating Columbia Circle's Adaptive Reuse

6.1. Reimagining Colonial Heritage at Columbia Circle

The adaptive reuse of Columbia Circle reconciles the restorationist and preservationist positions. For individual structures, architects sought to reverse the changes made during the industrial era and return them to their original form in the colonial era. This echoes the position of Victorian restorationists when they advocated for removing corrupting influences to purify spaces. However, architects avoided the excesses of Viollet-le-Duc's a priori principles, instead relying on meticulous research and surveys to piece together a genuine image that reflects historical reality. Furthermore, the government's emphasis on "readable architecture" embodies the preservationist belief that a building is a true record of history that we can scrutinize. In this case, however, architects were selective regarding what that history was. [83] While the colonial pasts of the Columbia Country Club, Navy Club, and Sun Ke Villa were considered essential to their historical and associative value, their experiences during the industrial era were considered traumatic and reversible.

A more inclusive policy was adopted for the overall complex. The colonial heritage and industrial heritage were regarded as indispensable parts of Columbia Circle's overall identity. Although SIBP structures did not enjoy the same level of legal protection as the colonial structures, architects still retained many SIBP structures, recognizing that each embodied a unique story that superseded the aesthetic value restorationists pursued. While delicately weaving together both

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[83] Baohua Li, "Opening 1056 Buildings, Demonstrating Principles of Readable Architecture," Shanghai Municipal People's Government, last modified June 14, 2022, https://www.shanghai.gov.cn/nw4411/20220614/9280e330a3c34eca9ec8981f147335cb.html.

preservationist and restorationist ideologies, architects also referenced modern concepts of architectural obsolescence. According to this view, the value of historic structures is not derived from their being "historic" but from their continual relevance to people. Therefore, the value of historic structures is not necessarily inherited, but rather created by repurposing them for new uses.

Obsolescence presents a strong case for Columbia Circle's adaptive reuse. While the exteriors of structures were deliberately restored to reflect the features of their day and age, their interiors were vastly altered to make them conducive to modern demands. These transformations were crucial in revitalizing the site economically by attracting businesses and consumers; by encouraging the integration of the site into the neighborhood and lifestyles of locals, architects prevented Columbia Circle from falling into a state of obsolescence. Columbia Circle's repositioning as a creative cultural space is a powerful adhesive that ties the disparate individual structures and resolves the historical juxtapositions of colonialism and nationalism.

The extrinsic changes to the exteriors and interiors of Columbia Circle's buildings are manifestations of a crucial intrinsic change. In a testament to the power of reinterpreting architecture, Columbia Circle has been reimagined as an open, inclusive, and diverse site with a local focus but an international message. The success of Columbia Circle lies in this proactive and daring reframing of heritage, specifically the colonial heritage that differentiates it from other industrial adaptive reuse projects in China. Connotations of exclusivity and inequality run deep through Columbia Circle's history—the Columbia Country Club, Navy Club, and Sun Ke Villa were emblematic of high society and the deep fissures between foreigners and locals, wealthy and poor, that existed during Shanghai's colonial years. Had the site not been repositioned and reinterpreted as an open and inclusive space, it could not have attained the economic and social success it now enjoys as a prominent cultural hub. The adaptive reuse strategy for Columbia Circle is both justified and necessary in providing its value and making it compatible with contemporary society.

The spatial interventions adopted during Columbia Circle's adaptive reuse were instrumental in cultivating its new identity. Bridging physical divides through path connections and social divides through public spaces allowed Columbia Circle to erase people's restrictive perceptions and engrain the site into the community. Columbia Circle has become a living room for the neighborhood, achieving social sustainability by promoting well-being and strengthening collective identity.

6.2. Columbia Circle as a Microcosm of Shanghai

The adaptive reuse of Columbia Circle is far greater than a local community project. The distinctive architectural heritage from different eras of Shanghai's history lends itself to the cultural agenda of Shanghai authorities. Notably, the focus on restoring the external appearance of heritage architecture suggests a conscientious view of history. Architects genuinely depict architecture as a symbol of respect and a demonstration of the diverse roles Shanghai embodied throughout history. Each building has a different history and story, but they are woven together in a poignant reflection of the coexistence of old and new, domestic and foreign.

Culture is increasingly viewed as a driver of urban growth and redefined

to address social, economic, and political objectives.[84] It plays an indispensable role in city marketing, where cities aim to improve their competitiveness, attract investment, and elevate their international prestige through positive branding.[85] The rise of the creative city revolving around the creative class has made attractive promotion of a city's environment and values more important than ever. Convincing and sustainable branding requires a city to draw from authentic local values rather than imported or artificial narratives.[86]

Shanghai's motto, "all rivers run into the sea," is not only a play on words (Shanghai means "above the sea"), but a demonstration of how central inclusivity is to Shanghai's identity.[87] Promoting inclusivity as an integral Shanghainese value through public spaces conducive to the equal and open discourse of people from different backgrounds leads to shared development.[88] In this respect, culture acts as a medium of collective identity and thus encourages inter-communal understanding.

At the same time, Shanghai's culture is absorptive and eclectic at heart, renowned for its constant adaptations to shifting market demands and the fusion of Eastern and Western cultures.[89] Hence, the Shanghai government is increasingly looking into colonial heritage as a source of inspiration and exemplars for Shanghai's values. This process often involves reframing heritage and drawing out values embodied by heritage that are compatible with the modern image of the city. In this case, the inclusive, international, and cosmopolitan connotations were retained, and the exclusive connotation was removed.

Shanghai does not dwell on its history. It does not hold its heritage with the same reverence as Ruskin or Hardy. Instead, it is contemplative of bygone eras and the complex legacy they left behind. Culture makes a city more discernible and distinguishable, but before Shanghai develops a distinct culture, it must rediscover its heritage and values. The adaptive reuse of Columbia Circle is perhaps best viewed as part of this rediscovery, an introspection of the past and a vision for the future.

7. Conclusion

Columbia Circle is a local project with global ambitions. The revitalization of an exclusive space into a hub of communal interactions has served the community positively. This transformation was achieved through meticulous restoration, thoughtful interventions, and spatial reorganization. The varied public spaces created throughout the complex have become well-integrated into the neighborhood and a platform for interaction between visitors and locals. Architects did not conform strictly to preservation or restoration. Nor did they emulate Viollet-le-Duc in bringing structures to an ideal state of "completeness" by referring to the intentions of original architects, as the circumstances that gave

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[84] Steven Miles and Ronan Paddison, "Introduction: The Rise and Rise of Culture-led Urban Regeneration," *Urban Studies* 42 (2005): 833-39.
[85] Ronan Paddison, "City Marketing, Image Reconstruction and Urban Regeneration," *Urban Studies* 30 (1993): 341.
[86] Joaquim Rius Ulldemolins, "Culture and authenticity in urban regeneration process: Place branding in central Barcelona," *Urban Studies* 51 (2014): 3029.
[87] Zhiqiang Liao, Sheng Liu, and Dongfan Xi, "Culture + strategy toward an international cultural metropolis of Shanghai," *Urban Planning* 239 (2017): 96.
[88] Ibid, 98.
[89] June Wang and Shaojun Li, "The rhetoric and reality of culture-led urban regeneration—a comparison of Beijing and Shanghai, China," *International Forum on Urbanism* (2009): 881.

birth to Columbia Circle are now considered troubled and complicated. Columbia Circle achieves social sustainability by supporting community wellbeing and strengthening collective identity. Through use and enjoyment, it is reborn.

While the social transformation was commendable, this study argues that the cultural transformation was the most critical factor for Columbia Circle's success, for it provided the basis for reimagining the complex as an inclusive public space. The reinterpretation of Columbia Circle's architectural heritage responds to the discourse on the value and treatment of architectural heritage. In a discussion dominated by the fiery exchanges of 19th-century theorists, Columbia Circle offers a refreshing 21st-century take on the question of preservation and restoration. First, the adaptive reuse criteria made clear that the history of a building alone could not justify its value. Structures were selectively retained or transformed based on their potential to meet modern demands. Second, the associations between structures and specific eras of Shanghai's past were considered valuable. These structures were restored to accentuate their embodied distinctive characteristics, emphasizing their aesthetic form. Third, and most important, modern interventions united these disparate, even contradictory, historical structures under a reinterpreted identity. The cosmopolitanism from colonial heritage combined with the innovation from industrial heritage to formulate a diverse identity built on the foundations of inclusivity, internationalism, and progress.

Was the reinterpretation of Columbia Circle's identity justified? This study argues that it was not only justified but imperative. Columbia Circle has been liberated from the burden of its past to contribute to the demands of today, not only in a materialistic fashion but also in a spiritual one—a conception of what the future can look like for urban sites falling into obsolescence or mired in a troubling past. It has achieved timelessness by rising above the constraints of historical periods and events. By being conscientious and critical of history, Columbia Circle achieves progress and sustainability for the future.

Nevertheless, Columbia Circle's adaptive reuse also raises questions. While the reinterpretation of heritage was constructive at Columbia Circle, it is often used as a pretext for gentrification. What should we make of substituting one community for another deemed more desirable by developers? When we emphasize the aesthetic form rather than historical connotations, do we jeopardize the inherent value of historic buildings? These questions are especially relevant for historic buildings with a residential function—the Lilong of Shanghai, the Pueblo of Santa Fe, and the Trulli of Alberobello—and can be the target of future research.

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Circadian Rhythms and Breast Cancer: Exploring the Molecular Interactions of the CLOCK Gene with Estrogen Receptor Alpha

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Abstract

Breast cancer exhibits regional disparities potentially linked to disruptions in circadian rhythms prevalent in Western lifestyles. These inherent 24-hour cycles, influenced by modern societal habits, have been increasingly associated with various malignancies, prompting further exploration into their role in cancer onset and progression. This paper offers a thorough examination of the molecular relationship between circadian rhythms and breast cancer, combining a litERαture review with a proposed investigation. The objective of the investigations is to explore the role of the HAT activity of the CLOCK gene in chromatin remodeling responsive to estrogens and examine the potential implications of CLOCK's conserved NRID in hormonal signal-driven transcriptional complex formation, especially in relation to Estrogen receptor alpha. The proposed investigation utilizes Co-IP assays to assess CLOCK and ERα intERαctions across cell lines and ChIP experiments to probe CLOCK's binding to estrogen-responsive elements. RNA-Seq, qPCR, and estrogen treatments will be used to further elucidate CLOCK's influence on ERα gene expression and estrogen dependency. CLOCK's HAT activity, ATAC-seq, and NRID domain functionality were also systematically examined to understand their roles in chromatin remodeling, accessibility, and estrogen-dependent gene expression. Through this hypothetical investigation, we hope to enrich the understanding of the interplay between circadian rhythms and breast cancer, suggesting potential future thERαpeutic directions.

1. Introduction

Breast cancer represents a substantial and escalating global health concern, ranking as the second most commonly diagnosed cancer with a reported 2.3 million cases in 2020 [1]. The occurrence of the disease exhibits marked disparity across regions, with a four-fold higher incidence in Western Europe as compared to Middle Africa

and Eastern Asia [2]. This implies that elements of a modern Western lifestyle, such as altERαtions in endogenous circadian rhythms, commonly known as circadian clocks, could have an impact on the initiation and development of breast cancer. Circadian rhythms, characterized by cell-autonomous oscillations with an approximate 24-hour periodicity, are a ubiquitous phenomenon found across a wide spectrum of life, from unicellular entities to more complex organisms such as humans. These inherent timing mechanisms interpret diverse environmental (e.g., photic stimuli) and metabolic (e.g., nutrient intake) cues, subsequently converting them into molecular oscillations within individual cells [3]. These intracellular molecular oscillations give rise to 24-hour rhythms pervasive in nearly every tissue in the organism, thereby governing an array of biological processes. Such processes include, but are not limited to, sleep regulation, energy homeostasis, endocrine function, immune response, and cellular prolifERαtion [4]. Disruptions in intrinsic circadian rhythms, precipitated by factors such as sleep deprivation, nocturnal alimentation, chronic jet lag, and atypical work schedules—frequent characteristics in contemporary Western society—can lead to dysregulation of circadian timing mechanisms and consequent imbalances in physiological homeostasis. Such disturbances have been associated with a host of pathophysiological conditions in humans [5]. This includes an increased susceptibility to sevERαl types of malignancies, such as prostate, endometrial, colon, lung, ovarian, breast cancers, and hepatocellular carcinoma [6]. The relationship between circadian clock disorders and cancer has been a subject of controversy, with some previous epidemiological investigations revealing a lack of correlation between the two. However, recent research, including studies endorsed by the International Agency for Research on Cancer (IARC), has identified a clear correlation between circadian clock disorders and various malignancies, challenging earlier findings [7]. In 2017 the IARC named disturbed circadian rhythms as carcinogens. Particularly, studies have shown that both genetic and environmental disruptions of circadian rhythms can significantly alter the expression and function of numerous tumor suppressors and oncogenes in both host and neoplastic tissues [8-9]. This altERαtion can facilitate the initiation and progression of cancer. Moreover, circadian disruptions may lead to reorganization of host metabolic processes and immune responses, thereby creating an immunosuppressive neoplastic microenvironment across various types of malignancies [10-11]. Given these critical roles in cancer etiology and progression, circadian rhythms have emerged as a significant target for oncological prevention and treatment strategies. In recent years, a growing body of scholarly research has focused on exploring the potential thERαpeutic application of circadian clocks. This includes approaches such as enhancing inherent circadian rhythms, modulating the bioactivity of specific circadian clock molecules, and strategically timing the administration of anticancer pharmaceuticals to align with host or tumor-specific circadian rhythms [12].

   Circadian disruption represents a substantial and undERαppreciated public health concern with far-reaching implications for physiological and metabolic processes. Although there has been an uptick in public awareness regarding circadian influences on breast cancer, the precise molecular mechanisms underlying these associations remain elusive [13]. Existing research is limited, with few studies investigating the effects of altered circadian rhythms on oncogenic pathways. A substantial knowledge gap persists in characterizing the molecular basis of how the circadian system influences specific genetic types of breast cancer, and how altered clocks may exacerbate the disease [14]. Further exploration of the mechanisms linking clock genes to cancer is essential to unravel the complex interplay between an altered circadian system and factors such as rotating shift work. Comprehensive

understanding of these connections will be instrumental in devising more targeted and effective thERαpeutic interventions, marking a critical advancement in both the prevention and treatment of this prevalent disease.

Hence, this paper aims to delve deeper into the molecular mechanisms that may be at play during the intersection of circadian rhythms and breast cancer. Specifically, we propose and detail an investigation on the Histone AcetyltransfERαse (HAT) activity of the Circadian Locomotor Output Cycles Kaput (CLOCK) gene in modulating chromatin remodeling in response to estrogens in a circadian manner, and possibly how this function may become aberrant in pathological cell growth. Importantly, CLOCK contains a putative NRID (Nuclear Receptor IntERacting Domain) that is highly conserved among species. While evidence that the NRID of CLOCK is functional is still missing, NRIDs have been previously shown to be essential to the recruiting of the appropriate HAT to the transcriptional complex in response to a hormonal signal [15]. Thus, it is conceivable that Estrogen receptor alpha (ERα),which has been shown to intERact with sevERαl coactivators with HAT activity, may use CLOCK as a coactivator and requires the HAT activity of CLOCK to modulate gene expression in an estrogen-dependent manner.

1.1. Circadian Clock Genes and the Circadian Cycle

In mammals, the molecular circadian clock is comprised of three fundamental components: input pathways, which convey information from environmental cues such as light; a central pacemaker situated within the suprachiasmatic nucleus (SCN) of the hypothalamus; and output pathways that transduce commands from the central pacemaker into circadian oscillations, thereby regulating physiological and behavioral functions in periphERαl organs and tissues [16]. Within the SCN, numerous single-cell circadian oscillators are synchronized to formulate daily circadian outputs. The genERαtion of these circadian oscillations is principally mediated through two transcriptional/translational feedback loops (TTFLs) [17]. The primary TTFL involves key clock genes, including CLOCK and brain and muscle Arnt-like protein 1 (BMAL1), functioning as activators, and Period (PER1, PER2, PER3) and Cryptochrome (CRY1 and CRY2) acting as repressors. This intricate system initiates transcription in the morning with the transcription of the Bmal1 gene driven by RORα, resulting in the synthesis of BMAL1 protein. This protein forms a heterodimer with CLOCK, constituting the CLOCK/BMAL1 complex. This transcriptional complex specifically recognizes and binds to CACGTG E-box sequences within the promoters of the Per and Cry genes, thus enhancing their expression (Figure 1). Concurrently, the CLOCK/BMAL1 complex augments the transcription of Rev-erbα, a key factor that suppresses Bmal1 transcription, establishing a regulatory feedback loop (Figure 1). In the cellular cytosol, PER is subjected to phosphorylation by casein kinase 1ε and 1δ, followed by ubiquitination, leading to its prompt degradation. Despite the degradation process, CRY continues to accumulate, facilitating the formation of a stable PER/CRY/CK1 complex. This tripartite complex acts as an inhibitor to the CLOCK/BMAL1 transcriptional activity, thereby curtailing further expression of Per, Cry, and Rev-erbα genes (Figure 1). Subsequently, the phosphorylated PER and CRY proteins are lost through degradation, relieving the repression on Bmal1 transcription. This de-repression allows for an increase in BMAL1 levels, effectively initiating the next circadian day [18]. A secondary TTFL is predominantly regulated by the transcriptional activation of the retinoid-related orphan receptors (RORs a, b, c) and repression of REV-ERBα/REV-ERBβ (Figure 1) [19]. This network, in conjunction with additional

kinases and phosphatases, imparts robustness to the circadian system, rendering it resilient to environmental perturbations. Furthermore, these mechanisms contribute to the maintenance of precise circadian timing and facilitate phase adjustments to align with local physiological conditions, thereby epitomizing the complexity and adaptability of the mammalian circadian system [20].
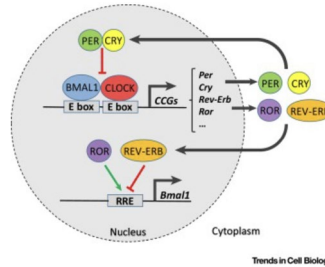
Figure 1: *TTFLs of Key Clock Genes and Associated Processes (taken from [21]).*

## 1.2. Epidemiological Studies on the role of Circadian Rhythms in Breast Cancer

The link between changes in circadian rhythm and breast cancer, initially recognized in the 1960s, has been a focal point for scientific exploration [22]. Over the last two decades, this relationship has been further elucidated through a series of epidemiological studies, highlighting the prevalence of hormone-related breast cancer in women engaged in irregular shift work, such as nursing professions [23-29]. Particularly, the risk has been shown to be exacerbated by factors such as starting night shifts before a first pregnancy and exposure to high levels of ambient light at night [30-31]. Irregular shift patterns, which mix night and day shifts within a week, were shown to cause more pronounced circadian disruptions than continuous night work. Complementing human studies, controlled experiments involving mice have revealed similar correlations. Simulated shift-work conditions, marked by weekly inversion of light cycles, significantly accelERαted tumor development in comparison to normal light/dark cycles [32]. These findings affirm that the disruption of sleep patterns, and thus the internal body clock, bears a direct influence on the rate of cancer development. Further enhancing our understanding is the focus on melatonin, a hormone with known oncostatic effects [33]. Its decreased secretion due to nighttime light exposure has been linked to more rapid growth of mammary tumors in rats and resistance to treatments such as tamoxifen—effects that could be reversed with melatonin supplementation [34-35]. In humans, these disruptions in melatonin secretion could lead to increased breast cancer risk and a lack of sensitivity to steroid thERαpy [36]. A pattern has emerged among nurses and other shift workers, where irregular schedules have resulted in elevated estradiol levels, further disrupting mammary estrogen signaling and promoting cancer development [37].

1.3. The Intersection between Circadian Rhythms and Breast Cancer

In studies involving Per2 loss-of-function mutant mice, mice with the mutation exhibit higher tumor incidence and show greater susceptibility to radiation-induced

malignant lymphoma compared with wild type [38]. Humans demonstrate reduced expression of Per genes in both sporadic and familial breast cancer cells, a phenomenon that may occur through methylation processes within the Per promoter regions. The proteins PER1 and PER2 are known to facilitate apoptosis and may act in vivo to inhibit breast cancer through the induction of apoptosis (Figure 2). Reduced expression of Per1 and Per2 in breast tumors leads to a diminished function of PER as a tumor suppressor [39]. Furthermore, these proteins can indirectly inhibit c-Myc transcription by repressing E-box-mediated transactivation via BMAL1/Npas2 [40]. A loss of Per2 results in decreased apoptosis, and thus accumulation of damaged cells, through an impairment of p53 (41) [41]. Per2 mutants also exhibit deregulation of CyclinD1 and Gadd45, all regulators of the cell cycle that are targets of c-Myc (Figure 2) [42-44]. The inhibition of PER1 affects key cell cycle regulators by intERαction with checkpoint proteins ATM and Chk2, and Per1 overexpression has been shown to decrease prolifERαtion in various cancer cell lines (Figure 2) [45]. The relationship is likely bidirectional as in U2OS cells, MYC has been shown to modulate the circadian system by binding to E-box elements, and elevated MYC expression can attenuate the circadian clock and foster prolifERαtion [43]. Additionally, CRY proteins are implicated in tumorigenesis via the cell cycle. The cell cycle suppressor WEE-1 is synchronized with PER, during periods when entry to the M phase is inhibited. Mice deficient in Cry genes display deregulation of Wee-1 and CyclinD1, leading to disrupted cell cycle regulation, a phenomenon observed in liver cells but not yet investigated in breast tumors [46].

Two metabolic regulators, SIRT1 and AMPK, act as cellular mechanisms that modify cell behavior in response to metabolic conditions, and both have connections to the circadian clock (Figure 2) [47–49]. SIRT1 functions as a histone deacetylase and is active when cellular NAD+ levels are high and inactive when NADH levels are elevated [50]. The deacetylation of p53 by SIRT1 inhibits its function and diminishes apoptosis, which could have potential consequences in oncogenesis (Figure 2) [51]. Both the cellular NAD+ ratio and SIRT1's deacetylase activity are subject to circadian regulation [52], and they can influence the core clock components, thus affecting circadian rhythms. The cellular energy status is represented by the AMP + ADP:ATP ratio. AMPK is phosphorylated by a kinase upstream when ATP concentrations are low [53]. When phosphorylated and thereby activated, AMPK governs sevERαl cellular processes such as glucose absorption, mitochondrial creation, cell growth, and also the circadian clock [54]. The cellular clock's regulation of AMPK activity leads to the breakdown of components in the negative portion of the core clock loop, specifically through the direct phosphorylation of Cry1 and CK1-mediated degradation of Per2 [49][55].
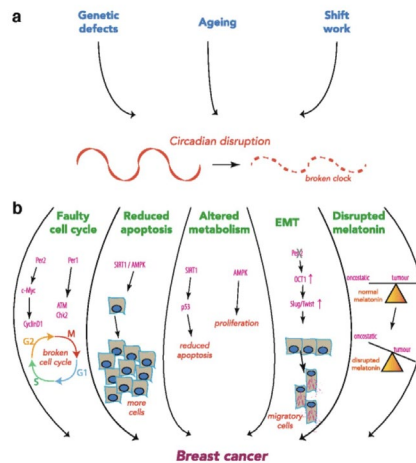
Figure 2. *Disruption of the circadian rhythm can contribute to the development of breast cancer (taken from [58]).*

1.4. CLOCK gene in Breast Cancer

1.4.1 CLOCK Gene SNPs and Breast Cancer Risk
The relationship between breast cancer susceptibility and the CLOCK gene is substantiated by specific single nucleotide polymorphisms (SNPs) found within this gene [57]. Distinct SNPs in the CLOCK gene are capable of directly altering the expression of genes that are integral to the regulation of cell cycle progression, such as CCL5. The hypermethylation of the CLOCK promoter region is particularly noteworthy, as it has been correlated with a reduced risk of breast cancer. In healthy control subjects, this hypermethylation is concomitant with decreased levels of the CLOCK protein.

1.4.2 Role of CLOCK and BMAL1 in Cell Cycle Regulation
CLOCK and BMAL1 proteins also activate the expression of "clock-controlled genes" (CCGs) [58]. The circadian clock has various conceptual and molecular aspects in common with the cell cycle [59]. This makes it especially significant that CCGs contain genes essential for controlling the cell cycle. Research has revealed that CLOCK-BMAL1 directly governs genes involved in cell cycle transitions like Wee1 (G2/M), c-myc (G0/G1), and Cyclin D1 (G1/S) [42] [46].

1.4.3 IntERαction of Circadian Regulators with Cell Cycle and DNA Damage Response Proteins
Furthermore, other circadian regulators closely connected to CLOCK seem to play roles in cell cycle control and DNA damage response. For example, PER1 intERαcts with ATM and Chk2 checkpoint proteins, while human Timeless protein intERαcts with Cry2 and cell cycle checkpoint proteins like Chk1 and the ATR-ATRIP complex. Despite recent connections between circadian proteins and the cell cycle, it's still unknown if these checkpoint proteins are altered by intERαction with core clock proteins, resulting in changes to their activities.

1.4.4 CLOCK's Histone AcetyltransfERαse (HAT) Activity and its Implications

A recent discovery added to this understanding by revealing that CLOCK possesses enzymatic function, specifically HAT activity. This allows CLOCK to induce changes in chromatin structure and create a state that enables gene expression activation [39]. Other HATs, like CBP and p300, known to acetylate non-histone targets, are identified as tumor suppressors. Though CLOCK is likely to acetylate non-histone proteins, its HAT function has not yet been connected to cell prolifERαtion control. However, CLOCK's ability to manage cell cycle genes indicates its acetylation role may be closely related to cell cycle control. Additionally, the association of its promoter region's hypermethylation with a reduced breast cancer risk, presents it as a potential oncogene rather than a tumor suppressor. In various cancer types, changes like translocation, amplification, overexpression, or mutation occur in genes that encode HATs. Mice with a CBP deletion may develop leukemia. SevERαl vital cell cycle proteins and transcription factors are known HAT targets, implying that HATs can influence cell prolifERαtion and differentiation in multiple ways, not just through chromatin remodeling. CLOCK's role as a HAT might be of special significance because of its influence over circadian physiology and cellular metabolism, possibly playing a central role in cell cycle regulation through direct intERαction and acetylation of regulatory proteins [60].

1.5 Estrogen Receptor Alpha in Breast Cancer

Variations in estrogen-associated signaling play a pivotal role in a significant proportion of breast cancers. Estrogen augments the growth of ER-positive breast cancer cells not only by upregulating genes that advance the cell cycle but also by downregulating genes that halt it. These modulations are orchestrated through systematic chromatin restructuring. Specifically, in the context of estradiol (E2), the estrogen receptor alpha (ERα) oversees the periodic association of coactivators and corepressors at the estrogen-responsive promoter region of the pS2 gene [60]. In the presence of E2, the activation of ERα sets off a cascade of signaling mechanisms, culminating in EMT and ECM transformation. For ER+ breast cancer, estrogen plays a pivotal role in advancing the disease by stimulating the PI3K/AKT signaling pathway [61]. In the ER+ breast cancer cell line MCF-7, calcium mediates the activation of estrogen signaling [62]. A recent report elucidates a tripartite association encompassing hormonal activation, chromatin architectural modulation, and cell cycle dynamics. In the presence of a specific ligand, ERα downregulates the expression of cyclin G2, an established negative modulator of cell cycle progression, by levERαging the recruitment of N-CoR and HDAC complexes.21. This phenomenon is congruent with datasets indicating the attenuation of ERα transcriptional activity by HDACs. Notably, the employment of HDAC inhibitors, namely TSA and 5-aza-dC, facilitates the epigenetic reprogramming of ER-negative breast cancer phenotypes to manifest ER-positive attributes (Figure 3). Subsequent to this ERα re-establishment, cells exhibit heightened sensitivity to estrogen antagonistic thERαpeutic regimens [60].
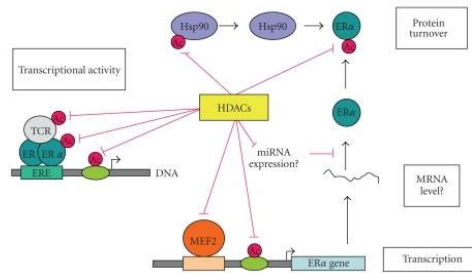
Figure 3. *Role of ERα in Breast Cancer (taken from [63])*

1.6 Study Rationale

The primary objective of the proposed study is to elucidate the role of the HAT activity of the circadian CLOCK gene in modulating chromatin remodeling in response to estrogens in a circadian manner and its implications in breast cancer pathology. Emerging research suggests that estrogens significantly influence the expression of key circadian genes, notably CLOCK [64]. Following the growing recognition of the complex relationship between circadian rhythms, hormonal signaling, and cancer, this study will employ tumorigenic and non-tumorigenic cell lines to examine the altERαtions in the intERαctions, functionality, and aberrations of the CLOCK gene and its NRID in response to estrogen signals. Specifically, it is hypothesized that ERα, which is known to intERαct with sevERαl coactivators with HAT activity, utilizes CLOCK as a coactivator and requires the HAT activity of CLOCK to modulate gene expression in an estrogen-dependent manner, and that this function may become aberrant in pathological cell growth.
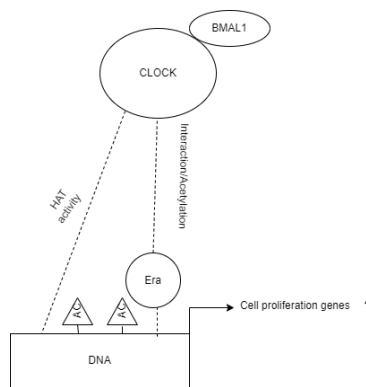
Figure 3. *Schematic representation detailing proposed investigation on CLOCK in breast cancer*

2.Methodology

2.1. Cell Culture

The study will employ human breast cancer cell lines MCF-7, alongside non-tumorigenic breast cell lines MCF-10A, which will function as controls. The MCF-7 and MCF-10A cell lines were obtained from the American Type Culture Collection (ATCC). In MCF-7 cells, wild-type ERα will is supplanted with mutations, specifically ERαD538G, giving rise to a state of partially estrogen-independent gene expression [65]. The cell lines will be cultured in media designated by the ATCC protocols, supplemented with 10% (v/v) fetal bovine serum (FBS) and 1% antibiotics, including 100 µg/ml streptomycin and 100 units/ml penicillin, at a constant temperature of 37°C within a humidified incubator maintained at 5% CO_2 concentration. To ensure the integrity of the experimental conditions, all cell lines will undergo testing to confirm the absence of Mycoplasma contamination, and authentication will be secured through the application of short tandem repeat (STR) assays.

2.2. siRNA Transfection

Cells will be plated at 60–70% confluence in 60 mm dishes. MCF-7 and MCF-10A will be transfected 24 hr (for RNA-seq) or 72 hr (for western blot) prior to the experiment with 20 nM siRNA targeting CLOCK (siCLOCK), or with non-targeting siControl (Dharmacon), as a control [66]. The siRNA oligonucleotides will be synthesized by GenePharma. Negative control will be scrambled siRNA targeting no known gene sequence. The transfection steps will be performed according to the manufacturer's protocols using Lipofectamine® RNAiMAX (Thermo Fisher Scientific, 13778030). The effectiveness of the CLOCK gene knockdown will be verified using qPCR and western blot analysis.

2.3. Co-Immunoprecipitation: Analysis of CLOCK and ERα Protein Interaction

Co-Immunoprecipitation (Co-IP) will be performed to analyze the interaction between CLOCK and ERα proteins. Cells will be subjected to lysis using a buffer comprised of 50 mM Tris–HCl at pH 7.4, 0.1% SDS, 0.25 mM deoxycholate, 150 mM NaCl, 2 mM EGTA, 0.1 mM Na_3VO_4, 10 mM NaF, 1 mM PMSF, and complete Protease Inhibitor (Roche) [67]. Following sonication and centrifugation, the supernatant will be collected. An immunoprecipitation assay will be conducted with an anti-CLOCK antibody, and any interacting partners, including ERα, with incubation overnight at 4 °C. The antibody-protein complex will be isolated using Protein A (Pierce), and the precipitates will be subsequently washed three times with the lysis buffer. The presence of ERα in the immunoprecipitated complex will be assessed using an anti-ERα antibody. Lysates and immunoprecipitates will be subjected to separation by SDS-PAGE, followed by immunoblotting, which will be conducted in accordance with the protocol provided by Thermo Fisher Scientific [68]. All antibodies will be obtained from Thermo Scientific.

2.4. Chromatin Immunoprecipitation: CLOCK Binding to Estrogen-Responsive Elements

Cells will be fixed with formaldehyde to cross-link protein-DNA complexes, and the reaction will be quenched with glycine. They will then be lysed in 500 μL of lysis buffer, and the chromatin will be sheared to fragments of approximately 200 to 500 base pairs using sonication. Cellular debris will be removed by centrifugation, and the supernatant will be precleared with Protein A/G-Sepharose beads that had been preblocked with salmon sperm DNA and BSA. Ten percent of the supernatant lysate will be stored as the "Input" source. The remaining lysate will be diluted and incubated overnight at 4 °C with an anti-CLOCK antibody. The antibody-chromatin complexes will be captured using Protein A/G-Sepharose beads and washed thoroughly in various buffers. The beads-bound chromatin will be released by intermittent vortexing and eluted in buffer [69]. RNase A and NaCl will be added, followed by overnight incubation at 65 °C. Proteinase K will be added, and the released DNA will be purified to a final volume of 50 μL using a purification kit. The binding of CLOCK to specific estrogen-responsive elements in the promoter regions of target genes in DNA from breast cancer and control cells will be assessed using qPCR with SYBR green reagent. PCR cycles will be maintained within the linear range of amplification [70]. Primer sequences for target genes will be designed through Primer3. Appropriate controls, including input controls and negative control IgG, will be included to ensure the specificity and validity of the results. All procedures will be conducted according to Thermo Fisher Scientific protocols, using reagents from the mentioned companies.

2.5. Gene Expression Analysis: RNA-Seq and qPCR Methods

The expression levels of specific ERα target genes will be quantified using qPCR, as already employed in earlier stages of the methodology. For an in-depth analysis of the impact of CLOCK modulation on ERα target gene expression, RNA-Seq will be performed. Total RNA will be extracted from the treated and control cell lines using the RNeasy Mini Kit (Qiagen) according to the manufacturer's instructions. The quality and quantity of the RNA will be assessed using a NanoDrop spectrophotometer and Agilent Bioanalyzer. A total of 1 μg RNA from each sample will be used to prepare libraries using the Illumina TruSeq RNA Sample Preparation Kit v2, following the manufacturer's guidelines. Sequencing will be performed on an Illumina HiSeq 2000 platform with 100 bp paired-end reads [71]. Raw reads will be aligned to the human reference genome using STAR aligner, and gene expression levels will be quantified using featureCounts. Differential expression analysis will be conducted using DESeq2, focusing on ERα target genes and associated pathways. Genes with an adjusted p-value < 0.05 and a log2 fold change > |1| will be considered as significantly differentially expressed. Multiple testing will be controlled using the Benjamini-Hochberg procedure.

2.6. Estrogen Treatment: Dose-Response Analysis of 17β-Estradiol Effects

Cells will be treated with varying concentrations of 17β-estradiol (E2) to analyze the effect on CLOCK and ERα interaction and subsequent gene expression. Treatment will be conducted following the protocol described by Guo et al. (2018). Various concentrations of E2 (e.g., 0 nM, 1 nM, 10 nM, 100 nM) will be prepared in ethanol, and cells will be treated with these concentrations for predetermined time points (6 hours). Control cells will be treated with an equivalent volume of ethanol without E2.

After 24 hours of treatment, the cells will be harvested and processed for further analysis through Co-IP, ChIP, qPCR, and RNA-Seq as described above [72]. The relationship between different concentrations of estrogen and its effects on the interaction between CLOCK and ERαa as well as on the expression of targeted estrogen-responsive genes, will be explored using non-linear dose-response curves. These curves will be created using Python software.

2.7. Investigation of CLOCK HAT Activity: Response to Estrogen at Circadian Time Points

In the investigation of the HAT activity of CLOCK in response to estrogens at 4 hour circadian time points, the study will first involve the extraction of nuclear proteins from both estrogen-treated and untreated cells. For the extraction of nuclear proteins, a NE-PER Nuclear and Cytoplasmic Extraction Kit (Thermo Fisher Scientific) will be used according to the manufacturer's guidelines. Following the extraction, the HAT activity will be analyzed using the EpiQuik Histone Acetyltransferase Activity/Inhibition Assay Kit (Epigentek). This colorimetric assay measures the acetylation of histone or specific peptide substrates.

Following the extraction, the CLOCK protein will be isolated from the nuclear extracts using immunoprecipitation. Briefly, nuclear extracts will be incubated with anti-CLOCK antibody attached to protein A/G agarose beads. After incubation, the beads will be washed to remove unbound proteins, and the bound CLOCK protein will be eluted from the beads. Nuclear extracts from both estrogen-treated and untreated cells at different circadian time points will be incubated with the provided substrates and reagents in the kit. The assay will be performed as per the manufacturer's instructions, with absorbance read at 450 nm using a microplate reader. The data obtained will then be analyzed to compare the HAT activity in extracts with or without estrogen treatment, taking into consideration circadian time points [73]. Depending on the distribution of the data, either unpaired t-tests or one-way ANOVA will be performed. Assumptions for the statistical analysis will be checked using Shapiro-Wilk (for normality) and Levene's test (for homogeneity of variance), and non-parametric alternatives will be employed if these assumptions are violated. Post-hoc tests, including the Bonferroni correction, will be utilized for multiple comparisons, with analyses being conducted at a significance level of $\alpha = 0.05$ using statistical software.

2.8. ATAC-seq Analysis: Estrogen-Induced Chromatin Accessibility Changes:

Cells will be harvested for ATAC-seq analysis. The isolated nuclei from the cells will be resuspended in lysis buffer and incubated on ice before being centrifuged to obtain the pellet. The isolated nuclei will then be treated with the transposition reaction mix from the Nextera DNA Library Prep Kit (Illumina), followed by incubation at 37°C to allow the transposase to fragment the DNA at accessible regions. Transposed DNA will be purified using a DNA purification kit such as the Qiagen MinElute Kit, and amplified using PCR with Nextera primers [74]. The sequencing library will be prepared following the Illumina guidelines, including size selection to target fragments representing open chromatin. Sequencing will be performed using the Illumina platform, generating paired-end reads. The raw reads will be aligned to the human reference genome using Bowtie2, and accessible chromatin regions will be identified using the peak-calling software cMACS2. False discovery rates will be controlled using the Benjamini-Hochberg procedure.

2.9. Functional Assessment of NRID Domain in CLOCK:

The functional significance of NRID in CLOCK protein will be assessed by generating CLOCK mutants lacking this specific domain. Site-directed mutagenesis will be utilized to specifically target the NRID region within the CLOCK gene. A template plasmid containing the wild-type CLOCK gene will be isolated. Primers will be designed to flank the NRID region of interest, and PCR will be performed using a mutagenesis kit such as the QuikChange II Site-Directed Mutagenesis Kit (Agilent Technologies). The PCR conditions will be set to facilitate the deletion of the NRID region. The resulting mutated plasmid will be transformed into competent E. coli cells, and positive clones will be selected and sequenced to confirm the successful deletion of the NRID region [75]. These CLOCK mutants will then be transfected into the breast cancer cell lines using Lipofectamine 2000 (Thermo Fisher Scientific). The interaction of these CLOCK mutants with ERα will be assessed through Co-Immunoprecipitation (Co-IP), as previously described, and the effect on estrogen-dependent gene expression will be studied using qPCR.

3. Results[1]

## 3.1. Cell Culture and Authentication:

All cell lines would be cultured under the specified conditions and periodically tested for Mycoplasma contamination. The Mycoplasma testing results would confirm the absence of any contamination in all the cell lines used throughout the study. Additionally, STR assay results would authenticate that the cell lines used were indeed MCF-7, T47D, and MCF-10A, ensuring the validity of the subsequent experimental results.

3.2. siRNA transfection verification

The relative expression of the CLOCK gene, normalized to GAPDH, would be assessed in MCF-7 and MCF-10A cells through qPCR following transfection with siCLOCK, siControl, or scrambled siRNA. As depicted in Figure 4, the siCLOCK-transfected cells would be expected to exhibit a significant reduction in CLOCK gene expression compared to the siControl and scrambled siRNA-transfected cells in both cell lines. For example, the relative expression of CLOCK in the siCLOCK-transfected MCF-7 and MCF-10A cells would be approximately 0.2-0.3, indicating a 70-80% reduction in CLOCK gene expression. Conversely, the relative expression of CLOCK in the siControl and scrambled siRNA-transfected cells would be 1-1.1 for both MCF-7 and MCF-10A cells, indicating no significant change in CLOCK expression compared to the untreated control cells. Such results would confirm that siRNA transfection successfully reduced the levels of CLOCK mRNA in the treated cells, thereby confirming that the siRNA-mediated knockdown was successful at the mRNA level in both MCF-7 and MCF-10A cells.

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[1] All of the graphs and charts in the results section except the western blot and genome browse tracker were created using python.
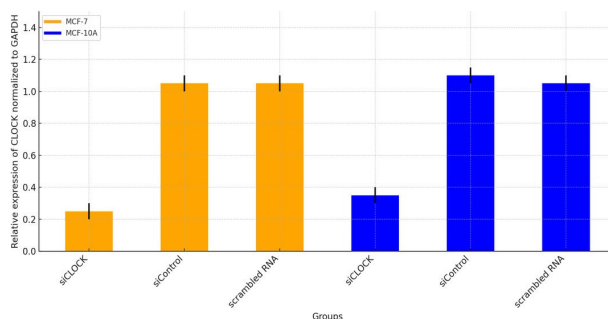
Figure 4. *Comparative Analysis of qPCR Results*
Post-Transfection with siCLOCK, siControl, or
Scrambled siRNA

A decrease in CLOCK mRNA levels as confirmed by qPCR does not necessarily equate to a corresponding reduction in CLOCK protein levels. The translation of mRNA into protein is subject to numerous regulatory factors, hence a decrease in mRNA levels does not invariably lead to a commensurate decrease in protein levels. Moreover, the CLOCK protein may possess a prolonged half-life, thereby delaying the reduction in protein levels even after a decline in mRNA levels. Consequently, while qPCR can validate the successful reduction of CLOCK mRNA levels by siRNA treatment, it does not furnish direct evidence of a concomitant reduction in CLOCK protein levels. It is therefore recommended to conduct Western blot analyzes to corroborate the knockdown at both the mRNA and protein levels. Figure 5 depicts the anticipated Western blot analysis of CLOCK protein expression in MCF-7 and MCF-10A cells, assuming a successful CLOCK knockdown.
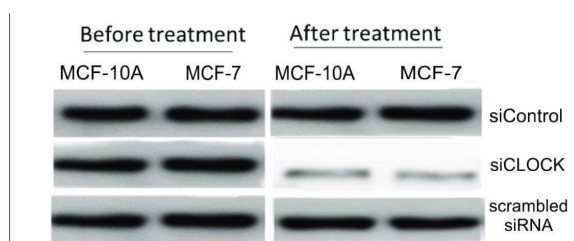
Figure 5. *Reduction of CLOCK protein levels in MCF-7 and MCF-10A cells transfected with siCLOCK. Each lane represents a different sample: lane 1, MCF-7 and MCF-10A cells transfected with siControl; lane 2, MCF-7 and MCF-10A cells transfected with siCLOCK; lane 3, MCF-7 and MCF-10A cells transfected with scrambled siRNA (adapted from [76])*

As depicted in the figure, the intensity of the CLOCK protein band would be significantly reduced in the siCLOCK-transfected MCF-7 and MCF-10A cells (lane 2) compared to the siControl and scrambled siRNA-transfected cells (lanes 1 and 3).

3.3. Co-Immunoprecipitation

In order to investigate the interaction between CLOCK and ERα proteins, Co-IP assays would be conducted using MCF-7 and MCF-10A cell lines, both with and without expression of the CLOCK gene. The MCF-7 and MCF-10A cells without CLOCK expression would serve as negative controls, while the cells with CLOCK expression would serve as positive controls. If there is an interaction between CLOCK and ERα as delineated in Figure 6, the quantity of ERα retrieved in the negative controls (MCF-7 and MCF-10A without CLOCK) would be minimal (e.g 0.1 ± 0.02 and 0.2 ± 0.03, respectively). Such a low amount in the negative controls would signify a high degree of specificity in the interaction between ERα and CLOCK, and minimal nonspecific binding or contamination. In contrast, the amount of ERα pulled down in the positive controls (MCF-7 and MCF-10A with CLOCK) would be significantly higher (e.g 1.8 ± 0.2 and 1.75 ± 0.3, respectively), indicating a strong interaction between ERα and CLOCK. If similar levels of ERα are pulled down in both MCF-7 and MCF-10A cells with CLOCK expression, it would suggest that the interaction between ERα and CLOCK is not cell-type-specific, but rather a general interaction that occurs in different cell types as is the case in Figure 6.These results would provide strong evidence for the hypothesis that there is an interaction between CLOCK and ERα.
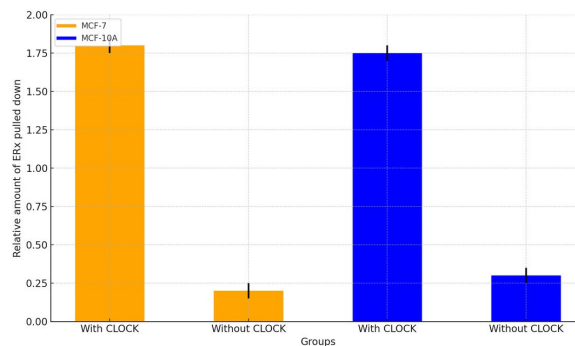

Figure 6. *Quantitative Analysis of ERα Pulled Down in Co-IP Assays with and without CLOCK Expression.*

3.4. Chromatin Immunoprecipitation

ChIP would be performed to assess the binding of CLOCK to specific estrogen-responsive elements in the promoter regions of target genes. The binding would be assessed in DNA from MCF-7 and MCF-10A using qPCR with SYBR green reagent. The target genes analyzed would be in the following ERE: Xenopus vitellogenin A2 (vitERE), Xenopus vitellogenin B1, Chicken apo very low-density lipoprotein II (apoVLDL II), and Human angiotensinogen. The results would be depicted through a qPCR analysis, where the cycle threshold (Ct) values of the CLOCK-bound DNA, input control, and negative control IgG would be compared for each target gene and each cell type. If CLOCK binds to the estrogen-responsive elements of these genes and potentially acts as a coactivator for ERα, one would expect that the CLOCK-bound DNA would have significantly lower Ct values than the negative control IgG for all estrogen-responsive genes analyzed in MCF-7 and MCF-10A cells with CLOCK (Figure 7a). This is because the Ct value is inversely proportional to the amount of target DNA in the sample, and a lower Ct value would indicate more binding of CLOCK

a)
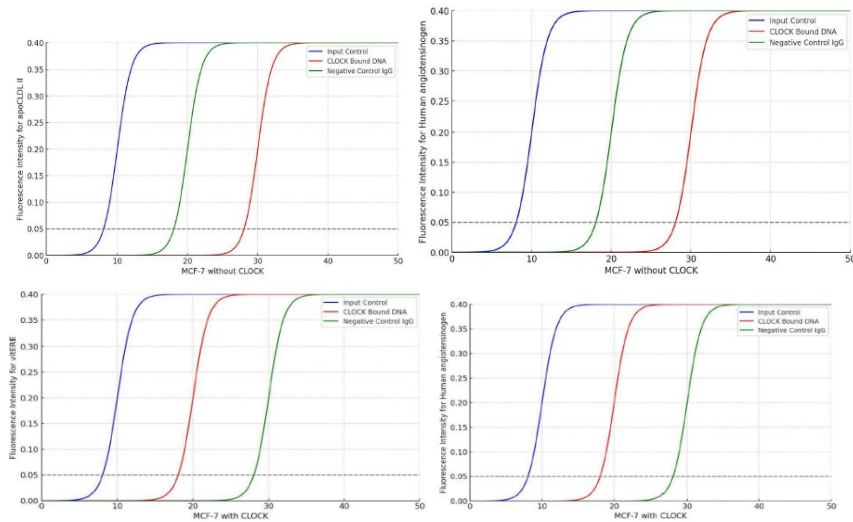
b)
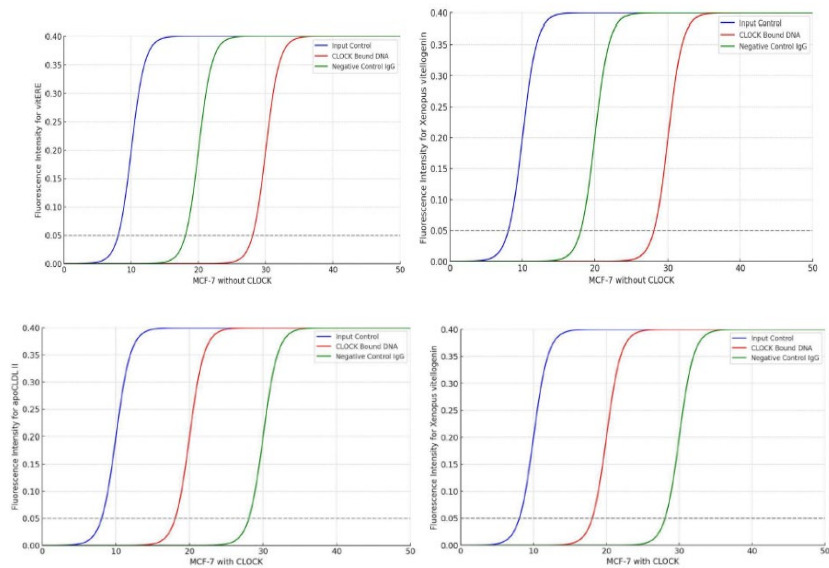
Figure 7. *a) Ct values of CLOCK-bound DNA, Input Control, and Negative Control IgG in MCF-7 and MCF-10A Cells with CLOCK; b)Ct values of CLOCK-bound DNA, Input Control, and Negative Control IgG in MCF-7 and MCF-10A Cells without CLOCK*

to the EREs. Conversely, in the absence of CLOCK in MCF-7 and MCF-10A cells, the Ct values for the CLOCK-bound DNA and the negative control IgG would be similar, indicating no specific binding of CLOCK to the EREs (Figure 7b). This would further support the specificity of the CLOCK and ERα interaction, as it demonstrates that in the absence of CLOCK, there is no binding, hence, no coactivation. The input control, representing the total chromatin before immunoprecipitation, is expected to consistently have the lowest Ct values across all cell types and target genes. This would confirm the specificity and validity of the results, as it demonstrates that the immunoprecipitation and qPCR are working correctly and that the differences in Ct values are due to specific interactions and not technical artifacts. These results would provide strong evidence that CLOCK is binding specifically to the EREs of target genes and potentially acting as a coactivator for ERα, thus supporting the hypothesis that ERα uses CLOCK as a coactivator to modulate gene expression in an estrogen-dependent manner.

3.5. Differentially expressed ERα target genes and identified through RNA-Seq and qPCR analysis

The heatmap would be used to represent the expression levels of the selected ERα target genes across the four cell types (Figure 8). If CLOCK expression is associated with increased expression of ERα target genes and the CLOCK gene has a regulatory role in the expression of ERα target genes, a statistically significant difference is expected between cells with CLOCK expression and those without. Specifically, all the selected target genes would exhibit increased expression in MCF-7 and MCF-10A cells with CLOCK expression, as denoted by the red color on the heatmap (Figure 8). Conversely, the expression levels of these genes would be significantly lower in cells lacking CLOCK expression, as indicated by the blue color on the heatmap. This would suggest a potential association between CLOCK expression and the upregulation of ERα target genes.

Figure 8. *CLOCK Expression Associated with ERα Target Gene Expression in MCF-7 and MCF-10A Cells*

3.6. Estrogen Treatment

The extent to which the interaction between CLOCK and ERα is estrogen-dependent would be investigated in MCF-7 and MCF-10A cells with and without the CLOCK gene, following treatment with various concentrations of 17β-estradiol (E2) (0 nM, 1 nM, 10 nM, 100 nM) for 24 hours .The expression of four estrogen-responsive genes would be analyzed in MCF-7 and MCF-10A cells with and without the CLOCK gene, following treatment with E2 through qPCR . If the interaction between CLOCK and Era and the resultant effect on ERE is estrogen-dependent, the Co-IP assays would show a dose-dependent increase in the interaction between CLOCK and ERα in MCF-7 and MCf-10A cells with the CLOCK gene, in the form of a sigmoid curve E2 (Figure 9). In contrast, the interaction between CLOCK and ERα would be significantly lower in MCF-7 and MCF-10A cells without the CLOCK gene and will not show a significant increase with higher E2 concentrations. Given the context of breast cancer

progression, and considering that ER-positive breast cancers proliferate in response to the hormone estrogen, it was anticipated that if CLOCK functions as a coactivator in this process, the sigmoid curve of the MCF-7 graph (with CLOCK) would have a significantly steeper slope compared to the MCF-10A graph (with CLOCK) indicating a weaker response to E2 treatment as illustrated in Figure 9.
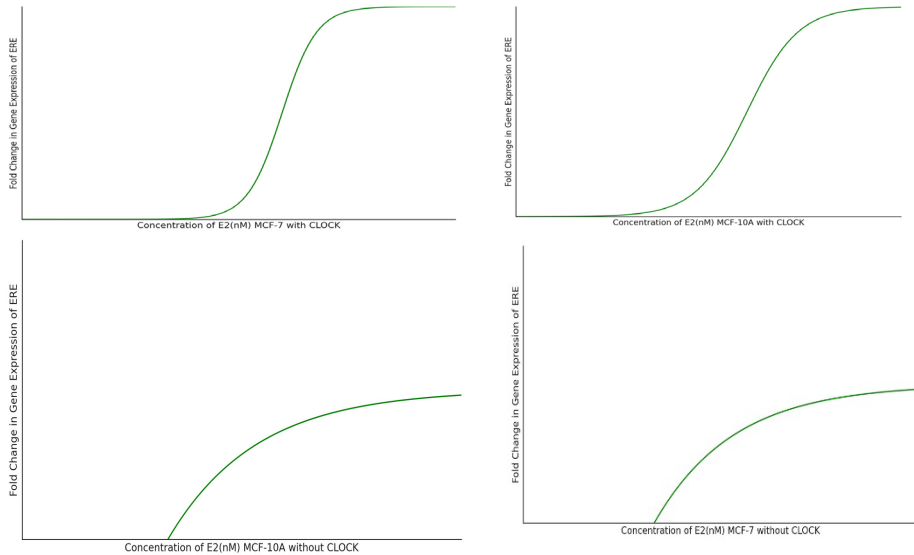
Figure 9. *Comparison of the E2 Dose-Response Relationship between MCF-7 and MCF-10A Cells with CLOCK Gene*

3.7. Investigation of CLOCK HAT Activity

In order to discern the differences between estrogen-treated and untreated samples at various time points and to shed light on how CLOCK's HAT activity is modulated by estrogen in a circadian rhythm context, the HAT activity of CLOCK in MCF-7 and MCF-10A cells world be measured at 0,4, 8, 12, 16, 20 and 0/24 Hours after treatment. If the HAT activity of CLOCK is modulated by estrogen in a circadian manner, it is expected that for both MCF-7 and MCF-10A with CLOCK, the estrogen-treated cells would consistently exhibit higher rates of HAT activity and would peak at a specific time point (Figure 10). Consistent with findings of the previous section and the idea that enhanced HAT activity can lead to hyperacetylation of histones, which is associated with an open chromatin structure and increased gene expression, it would be expected that the HAT activity would be higher and would be expected to peak at a different time hinting to a disruption in circadian control in MCF-7 (Figure 10). The differential activity of CLOCK in cancerous versus non-cancerous cells would contribute to the hypothesis that CLOCK plays a distinct role in the pathophysiology of breast cancer and may serve as a potential therapeutic target. It could also mean that the HAT activity of CLOCK may be altered during the transformation of normal breast cells into cancer cells. The absence of a significant relationship between estrogen treatment and HAT activity in cells lacking CLOCK would underscore the specificity of the observed effects to the CLOCK protein. Such findings would suggest

that the estrogen-dependent modulation of CLOCK HAT activity may play a role in the regulation of estrogen-responsive genes and could have implications for the development and progression of estrogen receptor-positive breast cancers.
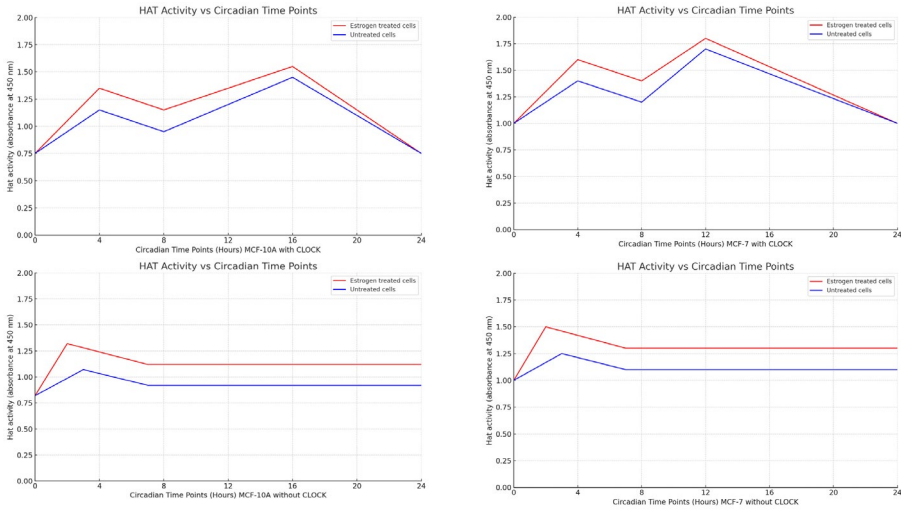
Figure 10. *Circadian Variation in CLOCK HAT Activity in Estrogen-Treated and Untreated MCF-7 and MCF-10A Cells*

3.8. ATAC-seq Analysis

Through the ATAC-seq results, patterns between estrogen-treated will be compared to discern any differences in chromatin accessibility, and pathway analysis will be conducted to understand how CLOCK-mediated HAT activity might be influencing chromatin accessibility, focusing on estrogen-responsive genes or regions. If the CLOCK gene modulates chromatin remodeling in response to estrogens, we expect that the MCF-7 cell line with the CLOCK gene and treated with E2, would exhibit pronounced augmentation in chromatin accessibility. This observation would be congruent with the aberrant chromatin remodeling phenomena frequently associated with pathological cellular proliferation. In contrast, the MCF-7 cells without CLOCK would manifest a decreased chromatin response post-E2 exposure, thereby emphasizing the pivotal role of the CLOCK gene in modulating estrogen-induced chromatin remodeling. The non-tumorigenic MCF-10A cells with CLOCK would display a moderate number of accessible regions, reflecting a typical non-cancerous chromatin response. This number would slightly decrease in the absence of CLOCK, hinting at the gene's impact on chromatin remodeling (Figure 11).
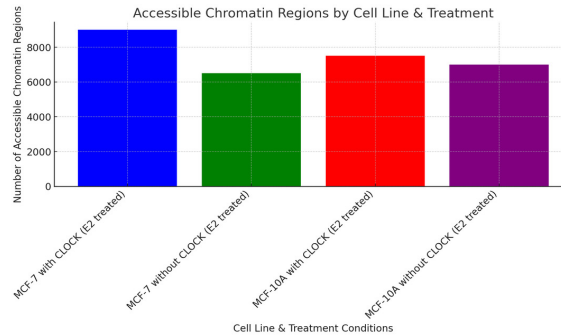
Figure 11. Comparative Analysis of Chromatin Accessibility in MCF-7 and MCF-10A Cells: The Role of CLOCK Gene in Estrogen-Induced Chromatin Remodeling

On the genome browser track, the differences would be further highlighted. Both MCF-7 and MCF-10A cells with the CLOCK gene would be expected to present pronounced peaks in estrogen-responsive genes upon E2 treatment. However, MCF-7 cells would reveal additional peaks in regions not usually associated with estrogen response, further reinforcing the aberrant nature of their chromatin remodeling. In the absence of CLOCK, both cell lines would manifest diminished chromatin responses, evidenced by fewer and less distinct peaks upon E2 treatment (Figure 12).

Figure 12. Genome Browser Track Analysis: Impact of CLOCK Gene on E2-Induced Chromatin Peaks in MCF-7 and MCF-10A Cells (adapted from [77])

Should this interplay be pivotal in breast cancer, the pathway enrichment analysis would reveal that MCF-7 cells with CLOCK, upon E2 treatment, demonstrate enhanced enrichment in estrogen-associated and other potential cancer-related pathways. Meanwhile, MCF-10A cells would show standard estrogen pathway enrichment. For both cell lines, lacking CLOCK would result in diminished enrichment in estrogen-responsive pathways (Figure 13).
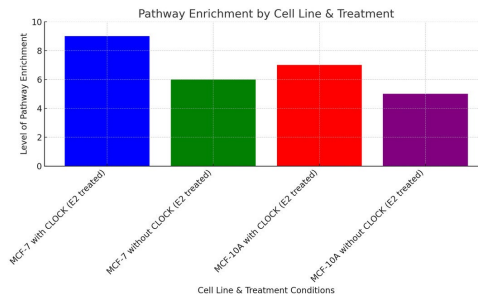
Figure 13. *Pathway Enrichment Analysis: Estrogen-Responsive and Cancer-Related Pathway Modulation by CLOCK in MCF-7 and MCF-10A Cells*

3.9. Functional Assessment of NRID Domain in CLOCK

The impact of NRID deletion on estrogen-dependent gene expression will be evaluated using quantitative real-time PCR (qPCR). The relative expression levels of an estrogen-dependent gene will be compared between breast cancer cell lines transfected with the wild-type CLOCK and the NRID-deleted CLOCK mutant. Should the NRID of CLOCK be pivotal in regulating estrogen-dependent gene expression, the qPCR results would reveal a notable reduction in the relative gene expression level of the estrogen-dependent gene in the NRID-deleted CLOCK group as opposed to the wild-type CLOCK group (Figure 11). For instance, the average fold change in the NRID-deleted CLOCK group could be 0.50 ± 0.15 (SD), in contrast to 1.00 ± 0.10 (SD) in the wild-type CLOCK group (Figure 14). It is important to normalize the relative gene expression levels to a housekeeping gene, such as GAPDH, and to compute the fold changes relative to the wild-type CLOCK group. A t-test statistical analysis should be performed to ascertain that the difference in relative gene expression levels between the two groups is statistically significant ($p < 0.05$). Under these circumstances, a significant reduction in the relative gene expression level of the estrogen-dependent gene in the NRID-deleted CLOCK group, relative to the wild-type CLOCK group, would likely indicate that the NRID of CLOCK is crucial for the optimal expression of estrogen-dependent genes.
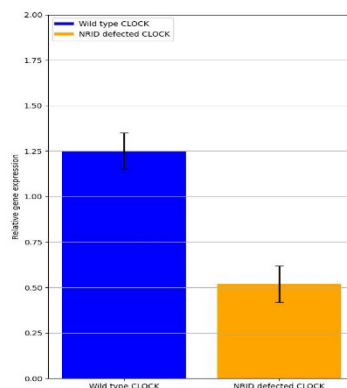
Figure 14. *Comparison of Estrogen-Dependent Gene Exp-ression in Wild-Type and NRID-Deleted CLOCK Transfect-ed Breast Cancer Cell Lines*

4. Discussion

The literature review and proposed investigation are aimed at elucidating the molecular interplay between circadian rhythms and breast cancer. The primary objective of the proposed investigation. was to discern the role of the CLOCK gene in modulating chromatin remodeling in response to estrogens, further exploring the potential aberrancies in this interaction during pathological cell growth. An underlying hypothesis guiding this exploration was the putative involvement of the CLOCK gene as a coactivator for ERα in estrogen-dependent gene transcriptional dynamics.If our hypothesis holds true, we would expect the following findings: Co-IP assays should reveal a direct and consistent interaction between the CLOCK protein and ERα across both MCF-7 and MCF-10A cell lines. Concurrently, ChIP experiments would likely demonstrate CLOCK's specific binding to estrogen-responsive elements, suggesting its role in guiding estrogen-dependent transcription. RNA-Seq and qPCR analyses should then amplify this understanding, indicating an upregulated expression pattern of ERα target genes in the presence of CLOCK. Subsequent E2 treatments might reveal a dose-dependent enhancement in the CLOCK and ERα interaction dynamics, with an anticipated heightened sensitivity to E2 in the MCF-7 cancerous cells. From the standpoint of CLOCK's rhythmic nature, its HAT activity could present a circadian regulation modulated by estrogen. However, aberrant patterns might emerge in the MCF-7 cells, alluding to CLOCK's potential role in breast cancer's oncogenic transformation and progression. Examining chromatin accessibility through ATAC-seq experiments, we would anticipate CLOCK playing a pivotal role in modulating chromatin landscapes in response to estrogens. Lastly, focusing on the NRID domain in CLOCK, its deletion could lead to a marked reduction in the expression of estrogen-dependent genes, further cementing the NRID domain's importance in the estrogen-dependent transcriptional architecture steered by CLOCK.

     The potential findings from this investigation could hold profound implications for both circadian biology and oncology. If the CLOCK gene indeed functions as a coactivator for Era, it emphasizes the significance of circadian regulation interwoven with hormonal pathways that govern breast tissue's health and pathology. This newfound understanding would underscore the exigency of circadian homeostasis in maintaining estrogen-mediated cellular processes. Given the documented perturbations in circadian rhythms in modern lifestyles, understanding this interplay could offer mechanistic insights into the epidemiological patterns of breast cancer prevalence in populations experiencing circadian disruptions.From a diagnostic perspective, perturbations in the rhythmic HAT activity of CLOCK or anomalies in its interaction dynamics with ERα could emerge as tangible molecular markers. Such markers would not only enhance the diagnostic precision but also prognosticate disease trajectory, facilitating early interventions. Therapeutically, should CLOCK's involvement in estrogen-mediated chromatin remodeling be validated, it propounds the gene as a potential pharmacological target. Targeted modulations of CLOCK-ERα interactions or chromatin modifications steered by CLOCK could unveil a new therapeutic paradigm, optimizing circadian and hormonal congruity within tumorous cells.While the focus remains on breast carcinogenesis, the principles derived could bear relevance across the oncological spectrum. Other hormone-responsive malignancies, like prostate and endometrial carcinomas, might exhibit analogous circadian-hormonal intersections, prompting a broader reevaluation of oncogenic pathways in light of circadian biology.

5. Limitations

Nevertheless, the proposed methodology for the study is not without its limitations. One significant limitation pertains to the cell lines employed in the study. The focus on MCF-7 and MCF-10A cell lines, which represent a particular subtype of breast cancer and normal mammary cells respectively, constrains the findings to a specific context, thereby questioning their broad applicability across the varied subtypes of breast cancer. Moreover, the predominantly in vitro nature of the experiments poses concerns about the physiological relevance of the findings. The absence of systemic hormonal fluctuations, immune system interactions, and tissue-specific contexts that are inherent to the in vivo environment might introduce a chasm between the observations and the actual biological manifestations in a living organism. Further complicating interpretations is the pleiotropic nature of the CLOCK gene, which assumes multiple roles across a spectrum of cellular processes. Delineating its specific interactions with ERα from its many other functions remains a challenging task, potentially introducing ambiguities in the results. A crucial consideration, especially given the rhythmic oscillations exhibited by circadian proteins, is the timing of the experiments. Selecting specific time points might inadvertently exclude vital temporal dynamics, leading to potential biases in discerning circadian influences. Lastly, while the cellular and molecular findings are poised to offer valuable insights, extrapolating these results to predict human physiological outcomes, especially in a diverse population with myriad genetic and environmental factors, remains a formidable challenge.

6. Conclusion

In conclusion, the intricate relationship between circadian rhythms, specifically the CLOCK gene, and breast cancer provides a promising frontier for understanding the underlying mechanisms of oncogenesis. Nevertheless, while the study would offer an exciting perspective on the interplay between the CLOCK gene, circadian rhythms, and breast cancer, it is a preliminary step. Further research is paramount to truly grasp the intricate relationship between circadian rhythms and hormonal influences in cancer.

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Global Warming and Altered Flowering Phenology: Ecological, Cultural, and Economic Dimensions

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Abstract

Climate change, a complex phenomenon with profound global ecosystem consequences, has led to temporal shifts in plants' traits, particularly in flowering schedules. Despite the extensive research on immediate climate change impacts, the subtler alterations in phenology—the timing of biological events—have received less attention. Phenology, a key to understanding climate change's ecological impacts, includes changes in flowering patterns. These shifts carry the potential for ecological and societal repercussions. Altered flowering times could disrupt ecological processes like pollination, impacting biodiversity and human livelihoods. Cultural traditions, agriculture, and economies are also interconnected with flowering timing, making an understanding of the phenomenon essential for mitigation and adaptation strategies. This paper comprehensively explores the consequences of shifting flowering times, spanning ecological, cultural, and economic dimensions.

1. Introduction

Climate change is recognized as a complex phenomenon with far-reaching consequences across global ecosystems. While specific impacts of climate change, such as sea level rise and temperature stress, have been extensively studied and documented, there is a less explored realm of its effects—the temporal shifts in life history traits exhibited by plants (Prevey, 2020). Specifically, alterations in the timing of flowering production and anthesis have been observed in response to changing climatic conditions. These seemingly subtle changes in flowering schedules, however, hold the potential to instigate a cascade of ecological and societal repercussions (Prevey, 2020; Bertin, 2014).

The primary focus of climate change research has largely revolved around the more overt and immediate consequences, and the subtler shifts in phenology have garnered relatively less attention. Phenology, the study of the timing of recurring biological events in relation to seasonal and climatic variations, is gaining increasing recognition as a powerful tool for comprehending the impacts of climate change on ecosystems (Prevey, 2020). In particular, the alteration of flowering schedules in response to changing climate patterns has emerged as a noteworthy area of study. Understanding these shifts and their broader implications is becoming paramount due to their potential to disrupt critical ecological interactions and human activities. Shifts in

flowering time have the potential to disrupt essential ecological processes, such as pollination. Pollination, a fundamental ecosystem service, underpins natural reproduction and agricultural production, ultimately shaping the availability of food resources for both wildlife and humans. The synchronization between flowering plants and their pollinators is finely tuned to ensure efficient and successful reproduction. Any deviations in this synchronization, induced by changing flowering patterns driven by climate change, could lead to reduced pollination success, altered plant-pollinator relationships, and potentially decreased biodiversity (Bartemous, 2011).

Furthermore, the impact of shifting phenology extends beyond ecological spheres, infiltrating various aspects of human life and society. Cultural traditions, agricultural practices, and economies are closely intertwined with the predictable timing of flowering events. Changes in flowering schedules can disrupt the timing of cultural festivities, alter agricultural crop yields, and introduce uncertainty into the livelihoods of communities reliant on seasonal activities.

Moreover, the phenomenon can facilitate the expansion of non-native species, potentially reshaping entire ecosystems and leading to the displacement of native flora and fauna. This paper endeavors to elucidate the impacts of shifting flowering times in response to climate change. The specific goal of this paper is to answer the following questions:

Is there evidence of a shift in flowering time that is tied to climate change?

Is there evidence of a mismatch between changing flowering times and pollinator emergence?

The aim of this work is to comprehensively assess the multifaceted consequences of phenological shifts by delving into their repercussions on ecological interactions, agricultural systems, cultural practices, and the potential spread of non-native species. This exploration will contribute to a deeper understanding of how climate change exerts its influence, not only through direct and immediate impacts but also through more subtle alterations that ripple through ecosystems and societies. As the world grapples with the challenges posed by climate change, a perspective that embraces the nuances of phenological changes is essential for devising effective strategies for mitigation and adaptation.

2. Climate Change

Shifts in temperature, precipitation, sea levels, and other climatic elements are all included in climate change, which is defined as the long-term transformation of Earth's climate patterns (IPCC, 2007). Numerous ecological processes, especially those in plant communities, are poised to be impacted by the interactions of these shifting factors.

In order to assemble scientific knowledge about climate change, the Intergovernmental Panel on Climate Change (IPCC) has assumed a pioneering role (Figure 1). Several of its in-depth assessment studies, including the Fourth Assessment Report (AR4), the Fifth Assessment Report (AR5), and the more recent Sixth Assessment Report (AR6), provide insights into the mechanisms behind climate change. These studies highlight how rising greenhouse gas concentrations, with carbon dioxide (CO_2) as the main culprit, are responsible for global temperature increases and other climatic changes (Springer et al., 2007; IPCC, 2021).
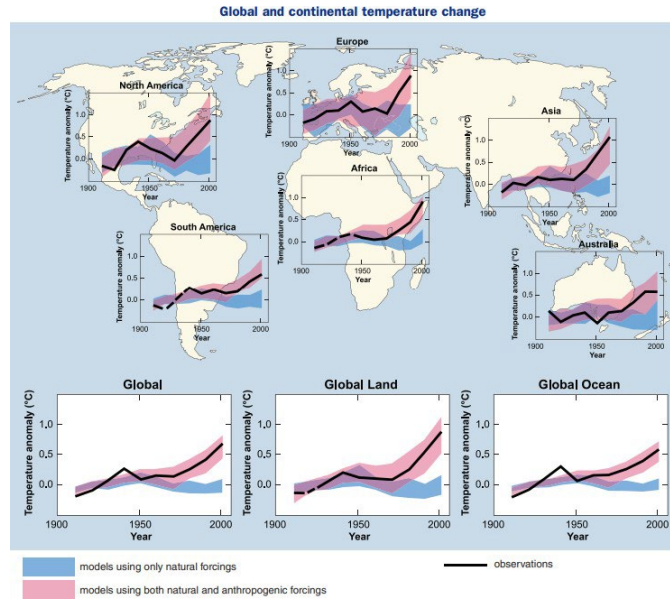
Figure 1. *A comparison is made between recorded changes in surface temperatures at both continental and global scales and the outcomes generated by climate models. These models are based on simulations utilizing either natural forces or a combination of natural forces and human- related factors. The decadal averages of observed temperature data are graphed for the time span between 1906 and 2005, indicated by a black line, that is aligned with the midpoint of each decade and referenced against the corresponding average between 1901 and 1950. Dashed lines denote instances where spatial coverage is below 50%. Within the visual representation, there are blue-shaded regions indicating the range between the 5th and 95th percentiles. These regions represent outcomes from 19 simulations performed by five climate models using solely natural forces like solar activity and volcanic events. Red-shaded regions encompassing the 5th to 95th percentiles depict results from 58 simulations conducted by 14 climate models, considering both natural forces and human-induced influences (IPCC, 2007)*
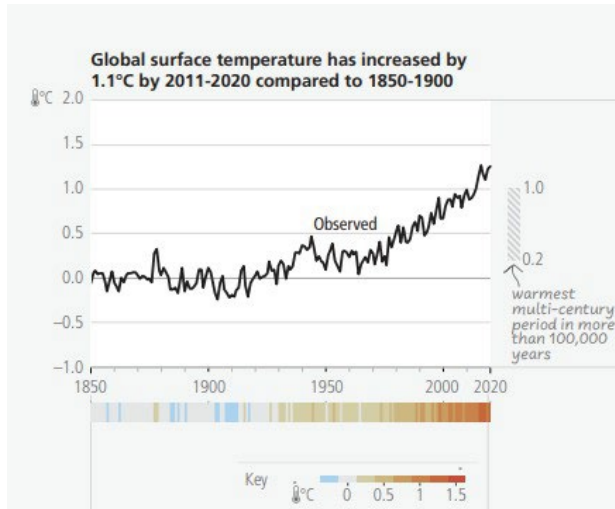
Figure 2. *The global surface temperature (shown as annual anomalies from an 1850–1900 baseline) has increased by around 1.1°C since 1850–1900 (IPCC, 2023)*

According to the data from the Synthesis Report of the Sixth Assessment Report, finalized by the IPCC during the 58th Session of the Panel held in Switzerland on March 13–19, 2023, global surface temperatures increased by 1.1°C from 2011 to 2020, compared to the period from 1850 to 1900 (Figure 2). This 1.1°C increase has implications for various factors, including ecological processes. Ecological processes are substantially impacted by temperature variations. Plants face a number of difficulties as a result of rising global temperatures, such as changing plant phenology by influencing blooming, coloring, and falling times. Plant-pollinator interactions and ecosystem dynamics are both impacted in a cascading manner by these changes (IPCC, 2014).

3. Phenology and Climate Change: Impacts on Plant Responses

The interplay between phenology and climate change serves as an indicator of the sensitivity of ecosystems to shifting environmental conditions. Phenology, which represents the temporal patterns of recurring biological events, is profoundly influenced by the altering climatic parameters associated with global warming (Bertin, 2015). The pronounced shifts in temperature and precipitation regimes inherent in climate change intricately regulate the timing of phenological events in plants. Elevated temperatures, characteristic of the warming planet, accelerate or decelerate the onset of critical phenophases such as budburst, flowering, and fruiting (Cleland *et al.,* 2006*)* (Table 1). These shifts can result in desynchronized interactions between plants and their environment, including pollinators and herbivores, leading to potential ecological mismatches. Such disruptions can reverberate through ecosystems, impacting species interactions, trophic dynamics, and ecosystem services. Understanding the relationship between phenology and climate change is paramount for predicting and mitigating the cascading ecological consequences that emerge from altering the timing of life history events in plants (Parmesan *et al.,* 2003).

Table 1. *Annual changes in the blooming, coloring, and falling periods of plants in Germany, Switzerland, Europe, Japan, and Northern Hemisphere. LU = leaf unfolding; LC = leaf coloring; LF = leaf fall. * Indicates the mean of significant trends only (IPCC, 2007)*

| Location	Period	Species/Indicator	Lengthening (days/decade)	References
Germany	1951-2000	4 deciduous trees (LU/LC)	1.1 to 2.3	Menzel et al., 2001; Menzel, 2003
Switzerland	1951-1998	9 spring, 6 autumn phases	2.7*	Defila and Clot, 2001
Europe (Int. Phenological Gardens)	1959-1996 1969-1998	Various spring/autumn phases (LU to LC, LF)	3.5	Menzel and Fabian, 1999; Menzel, 2000; Chmielewski and Rotzer, 2001
Japan	1953-2000	Gingko biloba (LU/LF)	2.6	Matsumoto et al., 2003
Northern Hemisphere	1981-1999	Growing season by normalised difference vegetation index (NDVI)	0.7 to 1	Zhou et al., 2001

Acknowledging the relationship between plant phenology and the specter of global warming, the Intergovernmental Panel on Climate Change (IPCC), a preeminent international body entrusted with the task of assessing climate change, embarked upon an endeavor to illuminate this relationship. This initiative culminated in the dissemination of a seminal report, which served as a compendium of collated and synthesized research endeavors devoted to the subject matter. In the canvas of this report, the IPCC published a synthesis of research on this subject. In the report they released, Germany, Switzerland, Europe, Japan, etc. examined the annual changes in the blooming, coloring, and falling periods of plants. The resulting picture confirmed the hypotheses supporting the major impact of climate change on plant phenology (Table 1).

      In a comprehensive investigation conducted by the IPCC, the study extended its focus to include the critical phenological trait of flowering in plants. Through the synthesis depicted in Table 2, specific plant species or indicators across 22 distinct regions were closely observed to discern and quantify annual alterations in timing (Table 2). The findings from this extensive analysis vividly underscored the substantial impact of global warming on the intricate dance of life within ecosystems. It became evident that the reverberations of climate change are not confined solely to the realm of plant phenology; rather, they have a wide-reaching influence, permeating through ecological systems, and manifesting in consequential shifts in animal behaviors, such as migration patterns. The observations made in this study serve as a poignant reminder of the intricate interplay between climate dynamics and the delicate rhythms of life on Earth. The alterations in flowering times of plants, a fundamental aspect of their life cycle, serve as a sentinel of broader ecological transformations in response to rising temperatures. This shift in phenology resonates across trophic levels, affecting not only plants themselves but also their interdependent relationships with a multitude of organisms, including herbivores, pollinators, and other wildlife. The cascading effects of these changes have the potential to reshape entire ecosystems, leading to shifts in species distribution, biodiversity patterns, and ultimately, the provision of crucial ecosystem services. Furthermore, the observed impacts on animal activities, particularly migration, are a testament to the profound and interconnected nature of Earth's living systems. The altered timing of flowering plants can disrupt synchronized ecological events, affecting the availability of resources for migratory species. This, in turn, may lead to mismatches in timing, potentially impacting the survival and reproductive success of these species. The implications of such disruptions extend beyond individual organisms, influencing the dynamics of entire populations and communities, ultimately shaping the fabric of biodiversity on a global scale.

Table 2. *Observed specific plant species or indicators across 22 distinct regions to discern and quantify annual alterations in timing. F = flowering; LU = leaf-unfolding; - advance; + delay. * Indicates mean of significant trends only (IPCC, 2007)*

Location	Period	Species/Indicator	Observed changes (days/decade)	References
Western USA	1957-1994	Lilac, honeysuckle (F)	-1.5 (lilac), 3.5 (honeysuckle)	Cayan et al., 2001
North-eastern USA	1965-2001 1959-1993	Lilac (F, LU) Lilac (F)	-3.4 (F) -2.6 (U) -1.7	Wolfe et al., 2005 Schwartz and Reiter, 2000
Washington, DC	1970-1999	100 plant species (F)	-0.8	Abu-Asab et al., 2001
Germany	1951-2000	10 spring phases (F, LU)	-1.6	Menzel et al., 2003
Switzerland	1951-1998	9 spring phases (F, LU)	-2.3 (*)	Defila and Clot, 2001
South-central England	1954-2000	385 species (F)	-4.5 days in 1990s	Fitter and Fitter, 2002
Europe (Int. Phenological Gardens)	1959-1996 1969-1998	Different spring phases (F, LU)	-2.1 -2.7	Menzel and Fabian, 1999; Menzel, 2000; Chmielewski and Rotzer, 2001
21 European countries	1971-2000	F, LU of various plants	-2.5	Menzel et al., 2006b
Japan	1953-2000	Gingko biloba (LU)	-0.9	Matsumoto et al., 2003
Northern Eurasia	1982-2004	NDVI	-1.5	Delbart et al., 2006
UK	1976-1998	Butterfly appearance	-2.8 to -3.2	Roy and Sparks, 2000
Europe, N. America	Past 30-60 years	Spring migration of bird species	-1.3 to -4.4	Crick et al., 1997; Crick and Sparks, 1999; Dunn and Winkler, 1999; Inouye et al., 2000; Bairlein and Winkel, 2001; Lehikoinen et al., 2004
N. America (US-MA)	1932-1993	Spring arrival, 52 bird species	+0.8 to -9.6 (*)	Butler, 2003
N. America (US-IL)	1976-2002	Arrival, 8 warbler species	+2.4 to -8.6	Strode, 2003
England (Oxfordshire)	1971-2000	Long-distance migration, 20 species	+0.4 to -6.7	Cotton, 2003
N. America (US-MA)	1970-2002	Spring arrival, 16 bird species	-2.6 to -10.0	Ledneva et al., 2004
Sweden (Ottenby)	1971-2002	Spring arrival, 36 bird species	+2.1 to -3.0	Stervander et al., 2005
Europe	1980-2002	Egg-laying, 1 species	-1.7 to -4.6	Both et al., 2004
Australia	1970-1999	11 migratory birds	9 species earlier arrival	Green and Pickering, 2002
Australia	1984-2003	2 spring migratory birds	1 species earlier arrival	Chambers et al., 2005

Additionally, some scientists confirmed this hypothesis with other studies. Among these endeavors, Robert I. Bertin's research merits attention. His work, concentrated in Worcester County, Massachusetts, examines the sensitivity of flowering times to climate shifts, encompassing methodological nuances in the collection of phenological records, the quantification of temporal shifts in flowering, and the exploration of interspecies variability. Bertin (2015) harnessed the potential of Monte Carlo simulations to scrutinize the statistical implications of varying sample sizes in the domain of flowering times. Over six decades, he documented alterations in temperature and flowering chronology in Worcester County, Massachusetts, harnessing herbarium specimens and direct observations while simultaneously subjecting hypotheses to empirical testing. Comparative analyses with analogous studies in the eastern expanse of North America enriched his investigation. The outcomes revealed a conspicuous uptick of 1.4°C in temperature across the 60-year span (Figure 3). Concurrently, the average flowering time hastened by 2.9 days, with early flowering species showing the most noticeable transformations. Predictive models forecast a shift of 4 to 10 days for species flowering in spring. Moreover, this inquiry revealed that factors such as native provenance and local tendencies held no sway over flowering times.
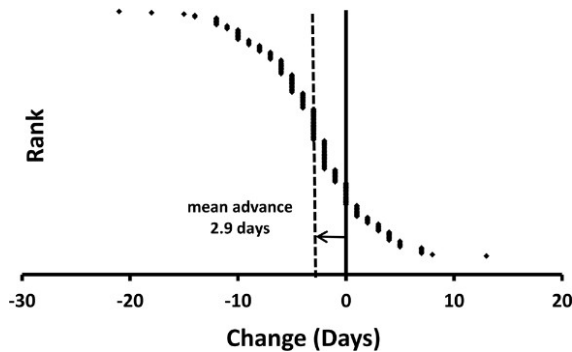
Figure 3. *Change in average flowering time of 186 species. Species were ranked from those showing the greatest advance to those showing the least advance. The difference in flowering times between the historical period and the recent period was highly significant (Bertin, 2015).*

In essence, the observed shifts in flowering times corroborate findings from studies conducted in cooler climes, showcasing deviations in spring-flowering patterns.

4. Pollination Dynamics as a Consequence of Climate Change on Phenology

One of the consequences of climate change on phenology lies within the realm of pollination dynamics. The timing of plant flowering and the availability of floral resources play a pivotal role in shaping successful pollination interactions (Bartomeus *et al.*, 2011; Burkle *et al.*, 2013; IPCC, 2021; Visser *et al.*, 2010). However, global warming-driven shifts in phenological patterns can disrupt the synchrony between flowering plants and their pollinators. Some researchers have found that early or delayed flowering, attributed to global warming-induced shifts in climate patterns, may lead to misalignments in the availability of floral resources and the foraging behaviors of pollinators. This observation suggests that the altered phenological schedules of plants directly impact the synchronization dynamics with their pollinator counterparts.

4.1 Flowering Time and Pollinator Mismatch

Burkle *et al.* (2013) undertook an investigative endeavor aimed at quantifying the extent to which global environmental changes spanning a span of 120 years had perturbed plant-pollinator interactions within a temperate forest understory community located in Illinois, USA. To achieve this, the researchers used a comprehensive dataset of insect visitors to plants meticulously documented and categorized by Charles Robertson in the late 1800s in Carlinville, Illinois, USA. The data from 2009 and 2010 were similarly collected and categorized, allowing for comparative analysis. The preeminent factor attributing to change was the moderate increase in climatic temperatures, which registered a rise of 2 degrees Celsius during the winter and spring periods.

As a result of this climatic transformation, the researchers observed pronounced alterations in the overarching network structure, spanning the temporal arc from the late 1800s to the years 2009 and 2010. Remarkably, only 24% of the original interactions persisted, underscoring a substantial loss of connections. However, the contemporary dataset illuminated the emergence of 121 novel interactions between plants and bees.

This transition from historical interactions to new ones translated to a net loss of interactions amounting to 46%. The observed shifts in interactions could likely be attributed to various factors, including alterations in the phenology and flowering times of plants, which might have led to a mismatch between the timing of floral resources and the presence of pollinators. In contrast, an alternative school of thought emphasizes the adaptive capacities of pollinators in response to changing flowering times. Proponents of this perspective argue that pollinator species possess the ability to adjust their behaviors and activity patterns to align with shifts in the phenology of flowering plants.

4.2 Flowering Time and Synchronization

In the study conducted by Bartomeus *et al.* (2011), the authors conducted a comprehensive examination of research papers focusing on bee-pollinated flowers. They conducted an analysis wherein they juxtaposed the timing of flowering events with the emergence patterns of bees.

Through this investigation, they unearthed significant temporal shifts over a span of 130 years. Specifically, the average flowering time exhibited an advancement of approximately 10.4 days. Notably, the research highlighted a particularly accelerated rate of early flowering alterations within the more recent 40-year period. Furthermore, the study delved into the relationship between springtime temperatures and the observed changes in flowering schedules. The authors discovered a correlation between the mean April temperature and the timing of flowering, elucidating the role of temperature in driving shifts in floral phenology. Crucially, when assessing the temporal patterns of bee emergence, the researchers revealed an alignment with the earlier flowering times. This alignment indicated that bees were adapting their activity schedules to coincide with the shifting flowering patterns, effectively bridging any temporal disparities. Consequently, the study demonstrated a dynamic interplay wherein the activity patterns of pollinators adjusted in response to the evolving flowering timings, thereby obviating the presence of temporal barriers.

As a result of the synthesis of these two studies, certain conclusions can be drawn. While select plant and pollinator interactions may exhibit a capacity for adaptation, others remain beholden to a temporal barrier. Given that these interactions are subject to temporal constraints, some results will occur.

4.3 Ecological Impact of Mismatches

The phenomenon of mismatches in flowering time and pollination exerts profound ecological repercussions, instigating shifts in species abundance, trophic interactions, biodiversity, community structure, and the balance of plant-pollinator mutualisms. These cumulative effects, extending to ecosystem services vital for human societies, underscore the importance of understanding and addressing these disruptions for the overall stability and resilience of ecosystems.

4.3.1 Shifts in Species Abundance and Competitive Dynamics

Mismatches in flowering time and pollination have been observed to trigger significant shifts in the competitive advantage of particular plants and pollinator species (Ollerton *et al.*, 2011). This phenomenon may lead to alterations in their relative prevalence within the ecosystem, potentially favoring species that are better adapted to the changing conditions. Consequently, this can set off a chain reaction of ecological consequences, influencing the distribution and abundance of various organisms throughout the broader ecosystem.

4.3.2 Effects on Trophic Interactions

Prolonged mismatches can have cascading effects on trophic interactions within an ecosystem. When a specific plant species fails to reproduce due to a lack of suitable pollinators, it disrupts the primary energy flow within the ecosystem (Memmott *et al.*, 2007). This disruption can reverberate through the food web, affecting species at different trophic levels. For example, herbivores dependent on the affected plant for sustenance may face food scarcity, impacting their populations and potentially cascading further onto their predators.

4.3.3 Loss of Biodiversity and Ecosystem Resilience

The persistence of mismatches over time may result in diminished populations of both plants and pollinators (Bartomeus *et al.*, 2013). This, in turn, can lead to a reduction in overall biodiversity within the ecosystem. A decline in biodiversity can have far-reaching consequences for ecosystem stability and resilience, as diverse ecosystems tend to be more adaptable to changing environmental conditions and disturbances.

4.3.4 Alterations in Community Structure and Functionality

Mismatches between flowering time and pollination can disrupt the web of relationships within ecological communities (Bartomeus et al., 2013). For example, if a key plant species fails to reproduce, it may directly impact species that rely on it for sustenance or habitat. This can lead to shifts in the composition and structure of the community, potentially favoring species that are less reliant on specialized pollination interactions.

4.3.5 Impacts on Plant-Pollinator Mutualisms

Mismatches can strain the delicate balance of mutualistic relationships between plants and their pollinators (Forrest and Thomson, 2011). As plants and pollinators evolve together, changes in flowering phenology can disrupt these tuned interactions. This can lead to reduced reproductive success for the affected plants and potential declines in pollinator populations, further exacerbating the mismatch.

4.3.6 Cumulative Effects on Ecosystem Services

The ecological impacts of mismatches extend beyond individual species or communities. They can also have repercussions for the services that ecosystems provide to human societies, such as pollination of crops and regulation of pests (IPBES, 2019). Prolonged mismatches can potentially compromise the stability and reliability of these critical ecosystem services.

4.4 Cultural Impact of Mismatches

Disruptions in pollination cycles pose a profound threat not only to ecological systems but also to the web of cultural practices and symbolism woven around specific plants, as exemplified by the Hanami festival in Japan, revealing the necessity of conservation efforts that encompass both natural and cultural dimensions (Miller-Rushing *et al.,* 2007)

4.4.1 Altered Phenology and Cultural Significance

The interplay between plants and their pollinators lies at the core of numerous global cultural practices. These enduring customs, deeply ingrained in local communities, hinge on timing regulated by nature's rhythms. When discrepancies arise, stemming from disruptions in pollination, a cascade of consequences ensues, potentially unwinding the very essence of these cultural practices.

4.4.2 Loss of Symbolism and Meaning

Within these cultural narratives, specific plants assume emblematic roles, carrying layers of profound symbolic significance. Their significance transcends the botanical sphere, encompassing spirituality and collective identity. However, the decline of these plants due to compromised pollination jeopardizes the very foundation of this symbolism, leaving communities devoid of their cultural touchstones.

The Hanami festival in Japan serves as a representation of this interplay between altered phenology and culture. This revered celebration, steeped in centuries of tradition, hinges on the blossoming of cherry trees. Its significance reverberates far beyond the visual spectacle, encompassing deep philosophical and cultural underpinnings. As a cornerstone of cultural expression, the Hanami festival not only holds immense meaning for local communities but also stands as a beacon for tourists worldwide.

Research conducted by Miller-Rushing *et al.* (2007) is a detailed example of research on how climate change affects plant phenology, specifically focusing on cherry trees in Tokyo, Japan. It discusses changes in flowering times over 25 years, attributing the earlier flowering primarily to an increase in February-March temperatures. The study also explores how closely related species respond to climate change, with most flowering earlier in warmer temperatures. Additionally, the research delves into the impact of warm years on flowering durations and variations among species.

The implications of this research extend beyond the scientific realm. They highlight the broader ecological consequences of altered phenology, including effects on cultural interactions.

Moreover, this study underlines the potential for evolutionary changes in phenology over time. It emphasizes the variability in flowering responses among unrelated species and addresses the importance of understanding how closely related species may differ in their responses to climate change. Additionally, the study acknowledges the role of cultural practices and traditions, as exemplified by the Hanami festival, which relies on the timely blossoming of cherry trees.

4.5 Economic Impact of Mismatches

Pollination is a fundamental ecological process, wherein pollen grains are transferred from the male reproductive organs (anthers) to the female reproductive organs (stigma) of a flower (Raghavan, 1997). This process is vital for the reproduction of flowering plants, including many crops of economic importance. The successful pollination of crops is directly linked to achieving optimal yields. When the timing of flowering in plants becomes misaligned with the activity patterns of their pollinators, it can lead to a reduction in the effectiveness of pollination. This, in turn, can result in diminished crop yields. Given the economic significance of agriculture, any decline in productivity can have far-reaching repercussions for the agricultural sector and its associated industries.

4.5.1 Mitigating Pollination Gaps

Managed Bee Colonies: In response to altered phenological patterns and potential pollination deficits, farmers often resort to integrating managed bee colonies into their agricultural practices. These colonies consist of carefully tended bee populations that are strategically placed in crop fields to enhance pollination (Fritsch, 1920). While this approach can be effective, it comes with its own set of costs and considerations.

4.5.2 Economic Burden of Managed Bee Integration

The incorporation of managed bee colonies involves expenses related to hive maintenance, transportation, and management practices. These financial investments can lead to an increase in the operational costs borne by farmers. Consequently, it is crucial to weigh these costs against the anticipated benefits in terms of enhanced

pollination and increased crop yields.

4.5.3 Market Dynamics and Consumer Impact

The availability of specific crops in markets hinges on successful pollination. Disruptions in this process can lead to fluctuations in the supply of these crops. This, in turn, can affect market stability, influencing both prices and accessibility for consumers. These market shifts can pose challenges for producers and consumers alike, necessitating adaptability in response to changing phenological patterns.

4.5.4 Secondary Industries Dependent on Pollinated Crops

Beyond primary agricultural production, a range of secondary industries heavily rely on crops that require effective pollination. This includes sectors such as honey production and specific segments of the food processing industry. The success of these industries is intricately tied to robust pollination practices. Consequently, any mismatches between plants and their pollinators can have a cascading impact on these associated industries, influencing their productivity and economic viability.

5. Results

This study provides comprehensive insights into the impacts of shifting flowering times in response to climate change. The investigation focused on two primary questions:

Is there evidence of a shift in flowering time that is tied to climate change?

The findings affirm a significant shift in flowering times associated with climate change. Over 60 years, a conspicuous increase of 1.4°C in temperature was observed. Concurrently, the average flowering time advanced by 2.9 days, with early flowering species exhibiting the most noticeable transformations. Predictive models project a shift of 4 to 10 days for species flowering in spring.

Is there evidence of a mismatch between changing flowering times and pollinator emergence?

The research reveals a dynamic interplay between flowering times and pollinator behavior. While shifts in flowering times were observed, there was evidence to suggest that pollinators, particularly bees, were adapting their activity schedules to align with the evolving flowering patterns. This adaptation helped bridge any temporal disparities and maintain synchronization between plants and pollinators.

Additionally, the study delved into the ecological, cultural, and economic consequences of these phenological shifts. The ecological impact encompasses shifts in species abundance, alterations in trophic interactions, potential loss of biodiversity, changes in community structure, and impacts on plant-pollinator mutualisms. These consequences collectively highlight the critical importance of addressing disruptions in flowering timing. On a cultural level, the study emphasizes the significant cultural implications of altered phenology, as exemplified by the Hanami festival in Japan. The decline in emblematic plants due to compromised pollination jeopardizes the symbolism and meaning embedded in cultural practices, potentially leaving communities devoid of their cultural touchstones. Furthermore, the economic implications of altered phenology, particularly in relation to pollination, are substantial. The study underscores the potential reduction in crop yields due to mismatches in flowering time and pollinator activity patterns. It also highlights the economic burden associated with integrating managed bee colonies into agricultural practices. Additionally, disruptions in pollination can have cascading effects on market dynamics, impacting both prices and accessibility for consumers. Secondary industries dependent on pollinated crops are also vulnerable to the economic repercussions of these mismatches.

Overall, this research provides a comprehensive understanding of the multifaceted consequences of phenological shifts, spanning ecological, cultural, and

economic dimensions. These insights are crucial for devising effective strategies for mitigation and adaptation in the face of climate change-induced alterations in flowering timing.

6. Future Studies

Future research endeavors in this field should adopt a comprehensive approach, integrating diverse methodologies and disciplines. Longitudinal monitoring of flowering phenology across a wide range of ecosystems will be essential in discerning patterns, trends, and potential thresholds in response to continued climate change. Advanced modeling techniques, incorporating not only climatic variables but also genetic and physiological factors, should be employed to enhance predictive accuracy. Investigating the genetic basis of phenological responses in various plant species will shed light on the potential for adaptive evolution in the face of changing environmental conditions. Furthermore, an expansion into multi-species interactions, encompassing not only plant-pollinator relationships but also predator-prey dynamics and interspecies competition, will provide a more holistic understanding of the broader ecological network and the intricate dependencies that underlie it. Beyond ecological considerations, future studies should delve more into the socio-cultural dimensions of altered flowering phenology.

Understanding how local communities adapt their cultural practices, traditions, and livelihoods in response to shifting phenological cues is crucial for promoting resilience and facilitating sustainable coexistence with changing ecosystems. Additionally, investigating economic strategies for resilience in agriculture is imperative, considering the far-reaching implications of altered phenology on crop yields and associated industries. This necessitates not only the evaluation of technological and managerial interventions but also an assessment of policy frameworks and market dynamics. Advancements in dynamic ecological modeling will be essential for simulating and projecting potential scenarios, allowing for the development of proactive strategies for adaptation and mitigation. Moreover, community engagement in conservation efforts, citizen science initiatives, and participatory action research can significantly augment data collection and provide invaluable local knowledge. Assessing the effectiveness of policy and management interventions, both at regional and global scales, will be crucial in refining and implementing evidence-based strategies. In a rapidly changing world, understanding cross-sectoral impacts will be paramount. Research endeavors should encompass assessments of how altered flowering phenology affects various sectors, including agriculture, forestry, tourism, and public health. Moreover, promoting global collaboration for data sharing and standardized methodologies will facilitate the aggregation of knowledge, enabling a more comprehensive understanding of the complex interactions between climate change and flowering phenology. This collaborative approach will not only enrich the scientific discourse but also inform evidence-based policies and adaptive strategies, ultimately contributing to the conservation and resilience of ecosystems in the face of ongoing environmental transformations.

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Urbanization and Food Waste in South Korea: An Ethnographic and Cultural Analysis of the Food Supply Chain Dynamics

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Abstract

Over the past several decades, rapid urbanization in South Korea has not only engendered a surge in food waste generation and changes in cultural practices, but also significantly influenced various biogeochemical processes and energy consumption patterns. While significant efforts have been made to mitigate the effects of food waste in South Korea, limited research exists on the internal processes impacted by urbanization that generate such waste. Thus, this study examines key components of the food supply chain and identifies changes in various consumer consumption patterns. This paper integrates a cultural lens to gain a unique understanding of the relationship between urbanization and food waste generation, particularly exemplified through Korea's traditional "banchan," kimchi. Ethnographic fieldwork such as interviews, observations, and data collection conducted in four regions across South Korea, varying in terms of urbanization, captured the real-time interactions and complexities between stakeholders within the food supply chain. This study utilizes these results to assess the scale of the impact of urbanization and its interconnectedness with environmental sustainability.

1. Introduction

The growing phenomenon of urbanization in South Korea has bestowed upon the nation newfound opportunities for growth, innovation, and expansion. With society expanding at exponential rates, there have been changes in consumer behavior and consumption patterns. According to a report by the National Assembly Research Service, the amount of food waste generated in South Korea was 16,032 tons in 2013, increasing by 31% to 21,065 tons by 2019 (Jeong, Pyun, and Chang, n.d.). Food manufacturing facilities further contributed to this issue by producing more than 1,400 tons of food waste daily (Jeong, Pyun, and Chang, n.d.). In addition, .25 of the food disposed of at the consumer level remains completely untouched. This trend has

profound implications on the biogeochemical cycles, namely the carbon, nitrogen, and phosphorus cycles, affecting greenhouse gas emissions as well as soil and water management systems. Therefore, Korea incorporated a series of measures to address food waste, providing a composting scheme to address the environmental effects of traditional food waste management methods (Lee et al. 2007). Nonetheless, the schemes did not counteract the lack of concern amongst individuals, companies, and organizations in curbing food waste, and thus, the persistent increase in food waste continued.

Urbanization brings about more than just changes in food waste generation; it also triggers a substantial transformation in Korea's cultural landscape. As a result, traditional customs and cultural practices face challenges in maintaining their relevance against the increasing allure of modernity. Simultaneously, newer and contemporary cultural elements have emerged. Despite this, research on food waste generation tends to focus on macro-level trends, disregarding the micro-level, cultural behaviors that contribute to food waste at various levels in the food supply chain. In the heart of South Korea, a nation renowned for its intricate culinary heritage, the traditional Korean staple, kimchi, is a striking representation of the challenges and opportunities created by urbanization within the food waste landscape. As urban areas expand, traditional kimchi that was once primarily produced in rural areas has relocated to urbanized and industrialized zones to meet the demands of customers. With this comes changes in Korea's cultural practices over time.

Recognizing the research gap concerning urbanization's influence on cultural and consumer behavior affecting food waste, this paper proposes a pioneering mixed methods framework that aims to provide nuanced perspectives on the drivers of food waste generation at the consumer stage of the food supply chain. With a cultural lens, this research analyzes and examines the consumption stage of kimchi whilst evaluating consumer behavior changes from four different locations in South Korea. Specific consumer behaviors symptomatic of urbanization, including the purchase of packaged foods, bulk buying, and impulsive buying were analyzed. The locations were determined based on the level of urbanization, where the first region is the most urban, the second region is moderately urban, the third region is moderately rural, and the last is the most rural. The fieldwork includes interviews, observations, and rigorous data analysis to comprehend the intricate interactions between the stakeholders that operate the food supply chain within these locations. Then, this study contains a comparative analysis with quantitative data on the scale of the impact of urbanization on waste generation for the different regions of Korea identified in this research. This analysis utilizes critical factors that were derived from the ethnographic study: the changes in food waste generation rates, consumer consumption patterns, and socio-cultural influences. Finally, this research sheds light on the extent of urbanization's reach into rural areas, the magnitude of disparities between urban and rural waste generation, and the quantification of the surge in food waste production. By illuminating the specific impacts of urbanization, particularly exemplified through the cultural traditions of Korea, this study provides crucial insights to inform policy initiatives and sustainable practices at various levels of the food supply chain.

2. Literature Review

2.1. Urbanization in South Korea

Urbanization denotes the redistribution of populations from rural to urban areas. The pace of urbanization varies from country to country: after the Industrial Revolution, developed countries found themselves going through intense urban growth while developing nations were in the throes of an urban transformation. South Korea was able to experience remarkable urbanization as an outcome of economic modernization, as macroeconomic successes brought about significant migration from rural to urban regions (Song, Dutt, and Costa 1994). The post-Korean War era, resulting in the government's implementation of the Five-Year Plans, saw a change in policy from import substitution industrialization to export-oriented growth. This acted as an investment in social overhead capital projects, such as the construction of highways or port facilities (Kang 1998), driving industrialization during the 1960s. Later, the "Saemaul Undong" movement of the 1970s was launched by former president Park Chung-hee. Diligence, collaboration, and self-help were critical values emphasized by this movement, which paved the way to rectify the disparity in the standard of living between urban cities and smaller villages. This further prompted the rural development and modernization of the Korean economy.

At the individual level, a variety of factors motivated citizens to participate in the development process. The first reason was economic pressure, which put pressure on young adults to seek jobs and opportunities (Kang 1998). Second was the aspiration for a higher quality education, which was prevalent in urban centers such as Seoul. With the notion of receiving a higher education being a prevalent theme in Korea, many sought a higher quality of education that was present mostly in urban areas. Lastly, large-scale infrastructure projects, the establishment of economic zones, and industrialization efforts created a magnet effect, drawing rural populations towards two specific cities: Seoul and Busan (Kang 1998).

Growth in modern infrastructure and connectivity ensued, including transportation networks, fast and widespread internet access, and an environment where information and resources flowed seamlessly and efficiently. Additionally, the 24/7 convenience store culture evolved, increasing the ability for consumers to fulfill their needs at any time (Hwangbo, Kim, and Cha 2017). Another advancement was retail innovation, where cities witnessed the emergence of innovative spaces and concepts that utilize unique and immersive shopping experiences that cater to the younger generations' disposition for novelty. For example, the Line Friends Flagship Stores all around Korea offer interactive displays, AR filters, and photo zones for customers to interact in creative ways. Such urbanization impacted demographic processes, cultural levels, income distribution, and much more, leading to a concentration of young, working-age population in urban areas (Hwangbo, Kim, and Cha 2017). At the same time, this demographic shift influenced cultural dynamics and social interactions that occurred in these urban centers.

2.2. Food Supply Chain

The food supply chain—a critical nexus between the production and consumption of agricultural products—has been the subject of extensive study due to its challenges associated with climate change, oil dependency, fair trade, and most importantly, food waste. Understanding this complex system is imperative for further study on the impacts of urbanization in various layers and stages of this ecosystem. The food

supply chain begins with agricultural production, where crops are cultivated and various livestock are reared while following local and international guidelines to ensure quality and food safety (Smith 2008). Next, raw materials are transported to processing facilities such as food factories and slaughterhouses to undergo numerous processes to result in intermediate or finished goods. Subsequently, the distribution, transportation, and logistics activities facilitate the movement of products across geographical regions. Finally, the retailing process is used to deliver products from the suppliers to the consumers, in which the food is finally purchased and consumed by a customer (Smith 2008).

Delving into each step of the process reveals underlying causes for food waste generation. During agricultural production, imperfect produce that fails to meet market standards is often discarded or left unharvested. The manufacturing stage reveals other inefficiencies causing food waste, such as peeling, trimming, or cutting that lead to the disposal of edible portions of food products (Porter and Reay 2015). Quality control measures, such as proactive quality control and reactive quality control where production anomalies or defects are removed, further contribute to substandard products unfit for distribution being wasted. However, food waste predominantly accumulates due to consumer behavior. At this stage, the culmination of decisions, attitudes, and habits shapes the trajectory of food waste from production to consumption. Consumer behavior and preferences influence every stage. However, consumer expectations and desires are erratic and variable during rapid urbanization. In South Korea, with urbanization's significant impact on society, this paper expects to find that there has been a shift in consumer behavior within the past decade, therefore expecting a direct relationship between urbanization and food waste generation.

In light of these observations, it becomes evident that the environmental consequences are significant due to energy consumption and biogeochemical processes that are intrinsically linked to food waste. During decomposition, food waste releases greenhouse gases such as methane and carbon dioxide, contributing to global warming. The nitrogen and phosphorus cycles are also impacted, as waste releases nitrogenous compounds into the environment. This leads to eutrophication in water bodies, where an excess of nutrients stimulates algal blooms that deplete oxygen in the water, harming aquatic life (Kahiluoto et al. 2011).

2.3. Evolution of Consumerism

Along with urban change comes cultural change; no country's culture is static. Some scholars often make the mistake of referring to a country's culture as a monolith that remains constant between generations. Evidence contrary to this belief is found in South Korea. Confucian ideas, filial piety, sacrifice, respect, and much more were all cultures characterized during the Joseon era in Korea (Park, Rehg, and Lee 2005). Today, such notions are predominant among the elderly, especially in rural areas. Now, a diverse set of beliefs exists among the younger generation in Korea. With urbanization, more specifically, Korean culture has shifted towards a culture that emphasizes consumerism. Consumerism means "the protection or promotion of the interests of consumers." Such a belief stems from the notable pivots in decision-making and purchasing that Koreans have made over the past several decades. For example, for the first time in Korean history, young adults became primary consumers of luxury brands such as Chanel and Louis Vuitton, whereas, in previous generations, those items were only obtainable by the older, wealthier generation. In 2017, 32% of all luxury brand purchases were made by young adults (Fendos 2018). Notable demographic differences also became apparent through the perspective of restaurant

experiences. Only 19% of Korean adults aged between 50 and 64 eat out more than once per day on average. By contrast, 48% of Korean adults aged between 19 to 29 eat out more than once per day. Moreover, the percentage of luxury automobile ownership by men has also undergone pronounced changes. In 2012, men in their 30s accounted for 24.6% of BMW purchases. In five years, that number has increased significantly, to 31.4% (Fendos 2018).

As seen, convenience, individuality, and ease of access are common themes that all have played vital roles in the cultural development of Korea. Simply put, the younger generation in Korea has become more self-oriented than their predecessors. While this alteration may elicit regret or sadness among the older generations, the prevalent disposition among younger Koreans is self-prioritization over familial obligations, which is a departure from traditional values. With globalization came lower wages and high debt, and yet an elevated yearning for opportunities amongst the younger generation. Consequently, traits commonly associated with rapidity have become prominent aspects of Korean citizens' outlooks, manifesting a proclivity for swift consumer behavior and impulsive purchasing decisions. As described in the previous examples, there has been a paradigm shift in consumer habits, where convenience and effectiveness have gained prominence in tandem with the evolving economic and social circumstances. As this landscape continues to transform, culture and behavior are redefined during the urbanization process.

2.4. Evolution of Culinary Culture

Certainly, urbanization's impact goes beyond consumerism, notably affecting the vibrant culinary culture of Korea. This culture is characterized by its depth, cuisine, and history, and is a genuine reflection of the country's identity. The intricacy of Korea's culinary practices has its foundation in agrarian roots. Originally derived from locally sourced ingredients and preservation techniques like fermentation, Korean cuisine embodies a profound link between sustenance and the natural environment (Kim 2016). A critical example, kimchi, is a fermented vegetable concoction produced through the meticulous selection of ingredients and a balance of flavors. Similarly, the tradition of "banchan," which is a collection of small side dishes that accompany the main meal, is a pillar in Korean dining. Ranging from pickled vegetables like kimchi to seasoned greens and marinated meat and proteins, banchan reflects Korea's emphasis on balance and variety. The evolution of this culinary identity has been influenced by both internal shifts and external interactions. For instance, the Japanese colonial era led to adaptations and changes to cooking methods and ingredients with the addition of seafood culinary techniques (Cwiertka 2006). Moreover, controlled resources and food distribution necessitated alternatives to homemade food such as processed and packaged foods.

3. Methodology

3.1 Research Design

This research employed a mixed-methods approach to investigate and study the influence of urbanization on consumer behavior, especially in the food industry. The study integrates qualitative ethnographic methods and quantitative data collecting to provide a holistic perspective on the understanding of food waste generation.

3.2 Qualitative Phase: Ethnographic Study

Participants of this study were selected from urban, moderately urban, moderately rural, and rural areas in South Korea. I selected Gangnam-gu as the urban area, as it is in the city of Seoul, known as the most rapidly urbanized and developed city in Korea. Incheon was the moderately urban region, a major port city currently undergoing urbanization while retaining some aspects of cultural heritage. Gyeonggi Province's Namyangju was the moderately rural region, which maintained a balance between urban expansion and agricultural practices. Lastly, Jeonju-si was the rural area, which represents the traditional and rural facets of South Korea. Several factors determined these locations, including economic activity, population density, and cultural development. While Seoul and Incheon are emblematic of high urbanization and busy lifestyles, Namyangju and Jeonju-si depict the rural countryside of Korea.

I carefully selected interviewees to represent a diverse range of individuals in terms of age from the four different regions. Interviews were conducted and living habits were observed for the various individuals. In Gangnam-gu, there were two office workers and two students. In Incheon, there were three office workers and two students. Namyangju had two farmers, one convenience store owner, and one student. Finally, in Jeonju-si, there were two farmers and two office workers. The interview sessions occurred at the interviewee's residences face-to-face. Choosing such a location allowed me to gain firsthand insights into the living conditions and practices, contributing to a richer understanding of the study's objectives. The selection of interviewees was approached with careful consideration in alignment with the study's focus on both the retail and consumer segments. Recognizing that both sides play important roles, the research sought to uncover a balanced narrative. Individuals were also selected from varying age groups, professional backgrounds, and urban contexts, aiming to provide diverse and accurate results on consumer behavior.

To account for potential bias during interviews, I standardized questions and had multiple fellow interviewers present at the time of the interview to guarantee impartial and accurate perceptions and records from the interviewees. Before initiating interviews, all interviewees confirmed consent to being a part of the research. Nonetheless, the identity of the respondents will remain anonymous, and appropriate pseudonyms will be used. Confidentiality will also be upheld not only in terms of the identities but also in protecting any of the sensitive information that was shared during the interview process. Further, during participant selection and interviews, cultural sensitivity was maintained to ensure that the cultural backgrounds, rituals, or practices were respected and understood within their specific contexts. Upon interviewing the participants, appropriate follow-up questions were asked, depending on the answers to the original questions.

Interview Questions for Consumers:
1. Can you describe your typical process of purchasing and consuming kimchi?
2. Have you noticed any changes in your food consumption patterns? If so, how have they changed?
3. What kind of Korean culture fosters the generation of food waste?
4. How often do you eat out and eat at home?
5. How often do you impulsively buy items and if so, why?
6. How often do you buy items in bulk, and if so, why?
7. Do you eat kimchi, and if so, how do you go about obtaining them?

In total, 17 interviews were conducted over the course of three weeks. Of these 17 interviews, 7 were office workers, 5 were students, 4 were farmers, and 1 was a

convenience store worker. The examination of frequency-based inquiries within the specific questioning framework centered on a metric of occurrences per week.

Eating out refers to the action of eating outside of an individual's home. Impulsive buying refers to consumer behavior in which individuals make unplanned and spontaneous purchases without prior consideration. Bulk buying refers to the purchasing of food items in larger quantities than immediately required.

In Gangnam-gu, there were two office workers and two students:
- Participant 1: Lee Ji-hoon, 32 years old, holds a Bachelor's degree in Business Administration from Seoul National University.
- Participant 2: Park Soo-jin, 28 years old, is currently pursuing a Master's degree in Marketing at Yonsei University.
- Participant 3: Kim Min-seok, 21 years old, is studying Computer Science at Korea University.
- Participant 4: Choi Eun-bi, 19 years old, is a Literature major at Ewha Womans University.

In Incheon, there were three office workers and two students:
- Participant 5: Yoon Mi-ra, 37 years old, graduated with a degree in Economics from Hanyang University.
- Participant 6: Jung Woo-sung, 45 years old, holds a Master's degree in Engineering from Inha University.
- Participant 7: Park Ji-young, 29 years old, is currently pursuing an MBA at Incheon National University.
- Participant 8: Kim Min-ji, 22 years old, is majoring in International Relations at Incheon University.

Namyangju had two farmers, one convenience store owner, and one student:
- Participant 9: Kang Dong-ho, 50 years old, completed a high school education and is a full-time farmer.
- Participant 10: Lee Mi-kyung, 62 years old, has a high school diploma and has been a farmer for most of her life.
- Participant 11: Kim Tae-hoon, 36 years old, owns a convenience store and has a Bachelor's degree in Economics from Kyung Hee University.
- Participant 12: Choi Ji-eun, 20 years old, is pursuing a degree in Environmental Science at Hankuk University of Foreign Studies.

Finally, in Jeonju-si, there were two farmers and two office workers:
- Participant 13: Han Seung-ho, 55 years old, completed vocational training and is engaged in farming.
- Participant 14: Park Sun-hee, 48 years old, has a high school education and runs a small family farm.
- Participant 15: Kim Yoo-jin, 30 years old, holds a Master's degree in Finance from Chonbuk National University and works as a financial analyst.
- Participant 16: Lee Ji-Eun, 34 years old, graduated with a degree in Management from Jeonju University and is a marketing manager.

3.3 Quantitative Phase: Data Collection

The second section of the mixed methods approach is the rigorous quantitative data collection and analysis. During this phase of the study, the same participants measured the amount of food waste they produced daily in kilograms within a two-week period, starting on Monday. At the same time, the participants were asked to

measure the frequency of eating out, impulsive buying, and bulk buying during this period. To account for the food waste generated from eating out, participants brought the remaining food back to their houses to dispose of in their food waste bins. Participants were requested to separate kimchi food waste from other types of food waste for the purpose of this study. Each participant was equipped with standardized guidelines, waste bins, and standard weighing scales to ensure consistent and accurate data collection of their waste generation daily. Participants without weighing scales were provided with the DS-166 weighing scale to ensure accurate results. The standardized guidelines provided specific instructions on the procedures to tare the scale with the empty bin before weighing their daily waste. Participants with any questions were advised to give a call to me. This process helped maintain the accuracy of the measurements by accounting for the weight of the bin itself. The study encompassed participants from all four regions, allowing for a cross-regional comparison of the patterns. With the extensive dataset collected from the participants across the four regions, waste generation patterns were noted and prominent trends were identified. A subset of the data was reviewed by peers in the field to ensure inter-rater reliability and consistency of the data analysis.

4. Results and Discussion

4.1 Hyper-Modern Individualism

The culture of a convenience-oriented lifestyle emerging from urbanization in Korea is intricately linked to the rise of individualism, a concept rooted in sociology and psychology. Hypermodern individualism embodies a heightened sense of and a focus on personal autonomy, instant gratification, and prioritization of immediate needs and desires over communal, and in this case, environmental considerations. While this is inherently associated with the modern urbanized experience, it drives both progress and decline. On the one hand, the rapid development of urban centers, technology integration, digital services, and hyper connectivity empower individuals to streamline their experiences specifically to their daily routines and preferences, thus providing efficiency for many citizens, along with urbanization. Nonetheless, what often comes is an intense focus on immediate gratification, and convenience can obscure the interconnectedness between actions and their consequences. All 13 interviews reveal deep-rooted philosophies of consequentialism in Korea. The analysis of the responses given by interviewees reveals that individuals value immediate positive outcomes, such as time saved, flavor experienced, or a temporary sense of accomplishment. Various forms of Korean culture evident in both urban and rural regions were demonstrated in the results.

Moreover, household structure dynamics emerge as a critical focal point in the discussions on consumer food waste in urban settings. Research has shown that consumer household food waste amounts were associated with demographic factors, such as household size, age, gender, income level, and amount spent on food (Evans 2011). There are numerous studies that indicate large households with younger generations are more likely to generate food waste than the rest of the population. Other studies suggest that household food waste is associated with household income levels. According to Qi and Roe (2016), high-income households tend to dispose of edible food due to concerns over health conditions resulting from stale foods. Nonetheless, another study indicated that low-income families generate more waste due to their buying behavior, such as buying fresh food products in bulk to save money (Evans 2011). Considering these intricate and sometimes contradictory findings, this

section bridges the gap between household structure dynamics, individualism, and food waste generation.

Table 1. *Average weekly food waste generated by each participant during the two weeks of the experiment*

Participant	Participant Number	Occupation	Region (Location)	Kimchi Food Waste (kg per week)	Normal Food Waste (kg per week)	Total Food Waste (kg per week)
Lee Ji-hoon	Participant 1	Office Worker	Gangnam-gu	0.23	0.42	0.65
Park Soo-jin	Participant 2	Student	Gangnam-gu	0.15	0.37	0.52
Kim Min-seok	Participant 3	Student	Gangnam-gu	0.02	0.18	0.20
Choi Eun-bi	Participant 4	Office Worker	Gangnam-gu	0.10	0.24	0.34
Yoon Mi-ra	Participant 5	Office Worker	Incheon	0.28	0.18	0.46
Jung Woo-sung	Participant 6	Office Worker	Incheon	0.20	0.40	0.60
Park Ji-young	Participant 7	Office Worker	Incheon	0.18	0.35	0.53
Kim Min-ji	Participant 8	Student	Incheon	0.14	0.32	0.46
Kang Dong-ho	Participant 9	Farmer	Namyangju	0.08	0.18	0.26
Lee Mi-kyung	Participant 10	Farmer	Namyangju	0.05	0.14	0.19
Kim Tae-hoon	Participant 11	Convenience Store	Namyangju	0.07	0.16	0.23
Choi Ji-eun	Participant 12	Student	Namyangju	0.09	0.20	0.29
Han Seung-ho	Participant 13	Farmer	Jeonju-si	0.06	0.15	0.21
Park Sun-hee	Participant 14	Farmer	Jeonju-si	0.04	0.11	0.15
Kim Yoo-jin	Participant 15	Office Worker	Jeonju-si	0.22	0.28	0.48
Lee Ji-Eun	Participant 16	Office Worker	Jeonju-si	0.10	0.36	0.46

4.1.1 Packaged Convenience Foods

South Korea's packaged food market is ranked the 15th largest in the world ("Sector Trend Analysis – Packaged Food Trends in South Korea" 2022). Major South Korean manufacturers such as Lotte, Nongshim, and CJ Cheil Jedang control significant portions of their respective sub-sectors in this industry. The widespread hypermarkets and supermarkets in Korea then serve as distributors of packaged food. Studies have found that time constraints are the driving factor in the rise in demand for convenience products and the demand for timely and efficient ways of obtaining shopping items. Convenience products are typically in smaller packaging, such as ready meals and instant noodles. The increasing percentage of women in the workforce, longer work commutes, and single-person households are also critical factors in the increase in the use of such convenience products.

In Gangnam-gu, the most urban region researched in this paper, the allure of packaged convenience foods was undeniable. Lee Ji-hoon stated during the interview,

"I have such a busy schedule, which practically forces me to visit convenience stores such as CU and GS-25 where I buy pre-packaged meals and snacks almost every morning." This correlated with the quantitative results, where Participant 1 generated the highest quantity of food waste over the research period of two weeks. *Table 1* depicts Lee Ji-hoon's food waste generation after the two-week period. When inquired about pre-packaged kimchi, she replied, "Pre-packaged kimchi products are so convenient and tasty at the same time, it made it impossible for me to not eat it along with the other food I normally eat." Participants 2 and 4 from Gangnam-gu had similar results, both stating that they purchase packaged food and kimchi from their local convenience stores. Both also admitted to normally being unable to finish a package of kimchi at meals. Participant 4 noted "The kimchi portions in the packaged products are often too much for me to eat in a single meal, especially since I live in a single household. Then I find myself too busy to preserve the leftover kimchi to eat later. I know this is wrong, but I just throw the kimchi away."

Similar results were demonstrated in Incheon, the moderately urban region in South Korea. Jung Woo-sung, an office worker, stated that he and his co-workers "appreciate the convenience of single-serving kimchi packages during office hours." In contrast, Park Ji-young, another office worker, articulated, "I've definitely noticed the excessive packaging as well as the pretty large kimchi portions. This is why I often share one kimchi package with my friends at work. But most of the time, I don't have an alternative to packaged kimchi when I'm rushed during work hours." This duality underscores the tension between individualism-driven convenience and environmental consciousness triggering a unique dilemma amongst many in South Korea.

Interestingly, this struggle was absent in the rural settings. The lack of convenience stores, fast commute times, and the presence of lenient work schedules allowed many individuals in Jeonju-si and Namyangju to foster responsible consumption practices. For example, Park Sun-hee, producing merely 0.15 kilograms of waste in one week, expressed, "My neighbors and I make kimchi as a community event. We have competitions over who makes the most flavorful kimchi. After that, we have a giant feast, and we try to share the leftovers among the different families in the neighborhood." This communal approach reflects a counterbalance to hypermodern individualism and packaged convenience. Furthermore, Choi Ji-eun, a student from Namyangju, expressed her love for Gimjang, the prominent Korean tradition of preparing and sharing kimchi and other traditional meals as a community. "I barely find the need to buy packaged food, especially kimchi, when everything is available to me in the neighborhood," said the student, endorsing Gimjang as a labor-intensive yet joyful communal activity. The persistence of traditional practices, resource-sharing, and resourcefulness in rural regions stands as a compelling counterpoint to eating packaged meals.

Interpreting these results reveals a dichotomy between community and individualism. The collective ethos of minimizing waste as well as the resourcefulness of sustainable practices in rural areas compared with the prioritization of convenience in urban areas leads to a disconnect between the collective impact on waste generation and personal choices. This highlights the rise in instant gratification in the urban setting, while collective well-being and patience are predominant characteristics in rural areas. These insights emphasize the importance of cultivating sustainable practices while respecting efficiency, cost-effectiveness, and organization.

4.1.2 Eating Out

Eating out in this section is defined as "eating meals provided by external entities." Within urban contexts, where food delivery is extremely common, these were regarded as eating out. Within rural contexts, communal meals, which were

customary, were not regarded as dining out due to the absence of external entities responsible for meal provision and arrangement. Eating out is often a symbol of status, meaning that a person who is eating out can afford to eat out. Other times, people desire to save time and money, and instead of going to the supermarket to buy ingredients and cook them, they travel to a restaurant. The rapid urbanization of South Korea significantly transformed dining habits, revealing an increase in the decision to eat out rather than prepare a meal in the house. Urban centers today offer a plethora of dining options, including fast-food chains, street vendors, and culturally diverse restaurants that cater to the manifold preferences of a cosmopolitan population.

Table 2. *Average frequency of eating out and eating at home of each participant per week*

Participant	Participant Number	Occupation	Region (Location)	Eating Out Frequency (per week)	Eating at Home Frequency (per week)
Lee Ji-hoon	Participant 1	Office Worker	Gangnam-gu	6	10
Park Soo-jin	Participant 2	Student	Gangnam-gu	9	8
Kim Min-seok	Participant 3	Student	Gangnam-gu	14	5
Choi Eun-bi	Participant 4	Office Worker	Gangnam-gu	13	7
Yoon Mi-ra	Participant 5	Office Worker	Incheon	3	13
Jung Woo-sung	Participant 6	Office Worker	Incheon	9	9
Park Ji-young	Participant 7	Office Worker	Incheon	11	9
Kim Min-ji	Participant 8	Student	Incheon	7	12
Kang Dong-ho	Participant 9	Farmer	Namyangju	3	15
Lee Mi-kyung	Participant 10	Farmer	Namyangju	3	15
Kim Tae-hoon	Participant 11	Convenience Store	Namyangju	5	13
Choi Ji-eun	Participant 12	Student	Namyangju	3	16
Han Seung-ho	Participant 13	Farmer	Jeonju-si	1	17
Park Sun-hee	Participant 14	Farmer	Jeonju-si	3	15
Kim Yoo-jin	Participant 15	Office Worker	Jeonju-si	2	16
Lee Ji-Eun	Participant 16	Office Worker	Jeonju-si	0	20

Regarding the frequency of eating out, *Table 2* illustrates the case of Choi Eun-bi, an office worker residing in Gangnam-gu. The findings indicate that she ate out at restaurants approximately 13 times a week. This notably high frequency of eating out provides insights into the urban dining behaviors prevalent among urban segments. She stated during the interview, "I really like eating outside a lot because of the diverse cuisines that are available to me." This trend is not exclusive to her in the urban context; comparable patterns emerged among other participants in the urban regions. The examination of dining-out frequencies across the four regions revealed

consistent trends. In Gangnam-gu, participants reported an average frequency of 10.5 times per week, while in Incheon, the average stood at 7.5 times per week. The manifestation of these patterns not only accentuates the prevalence of urbanization's influence on eating habits but also underscores its presentation across diverse urban settings. The findings from Namyangju revealed an average frequency of 4.75 times per week, whereas in Jeonju-si, the average was 2.75 times per week. These figures, considerably lower than those observed in urban contexts, reflect the pronounced variations in dining behaviors that correspond with varying degrees of urbanization. Han Seung-ho, a farmer from the rural region of Jeonju-si said during the interview that eating out was "completely unnecessary" because "food and ingredients are always available in the house" notably because of the proximity to various farmers.

Werf, Seabrook, and Gilliland (2019) conducted a study utilizing a multiple hierarchical regression analysis to predict consumers' actions toward reducing food waste. Interestingly, the results revealed a compelling correlation between dining behaviors and waste reduction efforts. Specifically, consumers who "eat out more frequently show a lower effort toward reducing food waste," influenced by portion sizes, low awareness of food waste generation while eating out, and food preference, which often results in discarded unflavored food components at multiple restaurants. This pattern was similarly observed during the interviews: unsurprisingly, all participants residing in Incheon expressed their indifference to simply not eating restaurant food that did not match their taste palette. Further, they revealed that when eating at Korean restaurants, the amount of leftover kimchi was "extreme." Finally, there is a correlation between *Table 2* and *Table 1,* where participants who eat out more generally produced greater amounts of food waste.

This issue is absent in rural settings, where eating outside is viewed as a rare activity. Park Sun-hee from Jeonju-si expressed her love for "community eating" but her disregard for "eating at busy restaurants" as she prefers a "calm and serene" environment. Nonetheless, Kim Yoo-jin from Jeonju-si expressed her desire to eat out, which aligns with the trends observed in urban regions. However, she is pragmatically limited by financial constraints. *Table 1* provides Kim Yoo-jin's quantitative contribution, as reflected in the production of 0.42 kilograms of food waste over one week. This comparatively heightened waste production could be attributed to her more "urban" mindset, which seems notably more substantial when compared to her fellow interviewees in Jeonju-si, underscoring the nuanced link between urban perspectives and waste generation. Perhaps the pull of urban aspirations prompts Kim Yoo-jin's preference for restaurant dining, a choice that might correspond with the higher food waste she produces, reflecting surplus consumption and disposal habits. Overall, the alignment between the research findings and the regression analysis bolsters the significance of the observed trends of eating out in waste production.

4.1.3 Impulsive and Bulk Buying

Another crucial aspect uncovered in this study is impulsive and bulk buying behavior. This may include activities such as purchasing discounted food items, getting bulk packages, or buying previously unplanned food ingredients or items. This often leads to the subsequent disposal of surplus food. According to a study by Stancu and Lähteenmäki (2022), impulsive food purchasing occurring at grocery stores or food markets is linked with "poor meal planning and shopping habits," and consumers impulsively buy items due to "in-store sales promotions, unavailability of smaller packaging, and over-estimation." Such sources of impulsive buying correlate with urban settings, where consumers are constantly exposed to a barrage of marketing strategies, such as promotions, displays, and advertisements. In addition, a study by

Hu, Chen, and Davison (2019) indicates that generally, the fast-paced nature of an urban environment amplifies the allure of quick and impulsive buying tendencies.

Table 3. *Average frequency of impulsive and bulk buying of each participant per week*

Participant	Participant Number	Occupation	Region (Location)	Impulsively Buying Frequency (per week)	Buying Items in Bulk Frequency (per week)
Lee Ji-hoon	Participant 1	Office Worker	Gangnam-gu	2	1
Park Soo-jin	Participant 2	Student	Gangnam-gu	1	0
Kim Min-seok	Participant 3	Student	Gangnam-gu	3	1
Choi Eun-bi	Participant 4	Office Worker	Gangnam-gu	4	2
Yoon Mi-ra	Participant 5	Office Worker	Incheon	1	1
Jung Woo-sung	Participant 6	Office Worker	Incheon	2	0
Park Ji-young	Participant 7	Office Worker	Incheon	3	1
Kim Min-ji	Participant 8	Student	Incheon	1	0
Kang Dong-ho	Participant 9	Farmer	Namyangju	0	1
Lee Mi-kyung	Participant 10	Farmer	Namyangju	0	2
Kim Tae-hoon	Participant 11	Convenience Store	Namyangju	2	1
Choi Ji-eun	Participant 12	Student	Namyangju	1	1
Han Seung-ho	Participant 13	Farmer	Jeonju-si	0	0
Park Sun-hee	Participant 14	Farmer	Jeonju-si	0	1
Kim Yoo-jin	Participant 15	Office Worker	Jeonju-si	2	0
Lee Ji-Eun	Participant 16	Office Worker	Jeonju-si	1	0

Many compulsive buyers report that most of their purchases are not needed, and some end up unused (Kwak et al. 2006). This was evident during the interviews with many individuals living in the urban regions of Korea. Choi Eun-bi, an interviewee with the highest number of impulsive buying frequencies, with an average of four impulsive buying and two bulk buying decisions, says, "Special or discounted offers are, you know, hard to ignore. I see a 1+1 sign on an item I completely don't need but by the time I arrive at the checkout, I find myself carrying at least three 1+1 items." Later during the interview, she admitted that the exact 1+1 food items she bought often "just lay around" even years after the purchase date. Kim Min-Seok, a college student living in Gangnam-gu, sheds light on bulk buying, stating, "I work part-time at a grocery store, and almost every time, I see so many customers buying stacks of drinks, snacks, boxes, materials, and just so many things for themselves. I ask them what it's for and their reply is 'It's for efficiency.'" The perceived need to be prepared for a fast-paced and uncertain lifestyle stemming from the urban environment is exemplified by Park Ji-young, an office worker in Incheon. He states,

"My schedule changes literally every single day. Living in arguably one of the busiest cities in the world creates a lot of unpredictable events in my life that I have to be prepared for, especially because of work. This leads me to buy numerous foods, especially canned food, in bulk." Such results reflect the "burnout culture" in Korea, which captures the intense and stressful nature of work, resulting in impulsive and bulk buying habits. By purchasing items both impulsively and in bulk, there is inevitably greater waste generated due to an increase in the amount of uneaten food.

In contrast to the urban findings, rural locations of Namyangju and Jeonju-si occasionally had individuals with zero instances of bulk or impulsive buying. Cultural themes of community-centric consumption, nongjang (agriculture and farming tied to the community's identity), and ingredient conversation were widespread. Farmers such as Kang Dong-ho and Han Seung-ho demonstrated a commitment to preserving farming and family heritage by taking care of the farm and sourcing resources directly from the farms. This resulted in absolutely no need for impulsive or bulk food purchasing.

While Korean culture permeates rural areas, ingraining sustainable consumer behaviors, the pattern of unnecessary purchases and accumulating items "for efficiency" is a recurring theme among urban consumers, underscoring the profound influence of the prevalence of promotional offers, discounts, and perceived future needs of certain items. Again, the theme of a dichotomy between communal values and individualistic tendencies is highlighted, and the heightened pace of life and the availability of diverse consumer options were determined to amplify these consumerism tendencies. As urbanization continues to shape modern societies, it becomes imperative to address this contrasting dynamic to foster more mindful and sustainable consumption practices across both urban and rural landscapes.

4.2 Culinary Culture

South Korean culinary culture is deeply rooted in the country's intensive history, and throughout significant historical periods and urbanization, it has developed unique characteristics. It is fundamentally distinct from Chinese or Japanese food cultures. Revealed in the paintings from the Chosun dynasty, food is depicted as a symbol of power used to control people, a health supplement, a way to express feelings and affections, and even a medium for communication with gods. Today, urban regions have seen a shift towards convenience foods and eating out at restaurants, reflecting the fast-paced lifestyle as well as the influence of Western food trends and diversity. However, traditional Korean dishes and food practices still hold importance in certain regions, and there is a growing interest in preserving and promoting authentic Korean cuisine.

4.2.1 Fermentation Practices and Food Preservation

The interviews revealed profound insights into consumer attitudes and behaviors concerning fermentation practices and food preservation in varying contexts. Among the notable findings was the discernible shift in the fermentation of kimchi. All interviewees were asked the question: "Do you eat kimchi, and if so, how do you go about obtaining them?"

Respondents frequently highlighted changes across generations toward kimchi production. For instance, Lee Ji-hoon, an office worker in Gangnam-gu, has a rich culinary heritage. She conveyed, "It's pretty well known amongst my close friends that my family is one of the families that pass on the recipes or 'secrets' of preparing kimchi. And now, of course, I took the initiative to pass it right on down to my own children, but what I realized was that they had absolutely no use for it." It can be

inferred from this statement that while the family represented a lineage that values preserving culinary traditions, a generational disconnect exists due to changing lifestyles and shifting consumer patterns. As noted, changes in the consumption of kimchi and food in general have had a significant impact on the production processes of traditional Korean food.

The transformation of living spaces from houses with ample outdoor space to cramped apartments also engendered the decline in traditional fermentation practices. Park Sun-hee, a female farmer from Jeonju-si identifying as Korean, mentioned the techniques she uses such as "Onggi Fermentation," which is where earthenware vessels are used to ferment various foods like kimchi. Solar drying and Jangdok were also kimchi preservation methods mentioned by the farmer. Nonetheless, respondents interviewed in both Gangnam-gu and Incheon uniformly identified a predominant challenge in the form of inadequate domestic space for traditional kimchi preparation. Furthermore, several interviewees from the urban regions exhibited a lack of familiarity with such traditional processes. These changes have implications not only for food preservation techniques but also for cultural identity and the generation of food waste.

4.2.2 Banchan

Banchan, an integral part of Korean culinary culture, reflects traditions that date back centuries. Banchan is essentially the collective name that describes the Korean side dishes, including kimchi, which are served alongside the main Korean cuisine. It is extremely common for people to serve side dishes that are locally sourced ingredients, and this has been a historical manifestation of regional flavors and family traditions. Both the qualitative and quantitative results suggest that urbanization has exerted a discernible influence on the consumption of food in Korea.

Kim Min-seok, a student living in Gangnam-gu stated, "During very big family gatherings, my grandma makes many kinds of banchan such as green onion, soybean sprouts, kimchi, seaweed, and a lot of other vegetables." When asked about daily life, however, he replied that his internship, college, and city life in general has introduced "convenience foods" such as "delivery and convenience store packaged foods." Additionally, Jung Woo-sung, an office worker living in Incheon noted during the interviews, "When I was little, I remember watching my mother and grandmother preparing all kinds of banchan, but now, there are small boxes at my local grocery store that sell like 8 different kinds of banchan in one box. To be honest with you, this is much better for me because I don't have to spend hours and hours preparing the side dishes." From this, there seems to be heavy production of "convenient" food items where, while the quality of the food is reduced, it is much more accessible and suitable for those living in busy, urban areas like Gangnam-gu.

However, Choi Ji-eun, another college student of Namyangju, fondly recalls the cultural significance of banchan passed through generations in her family. "My grandmother's kimchi, jeon, and namul recipes are precious to our family. They are cherished and passed down for generations. I find myself using the recipes to make banchan quite a lot of times when I'm at home." This reflects the enduring significance of banchan, Korean culinary culture, and traditions in general in rural regions.

In light of this, previously discovered patterns of consumption that were predominantly present in urban areas were determined to exist in rural regions as well. The labor-intensive cooking results in the excessive gathering of crops from local farms and markets in both Namyangju and Jeonju-si and often leads to leftover food from the banchan. The diverse dishes often lead to over-preparation, and due to small portions, there are often more than 10 side dishes prepared per meal. This results in leftovers when diners cannot finish all the side dishes.

5. Conclusion

This research has discovered critical insights into the relationships between urbanization, individualism, and food waste in South Korea. The study highlights the prevalence of hypermodern individualism in urbanized areas, where convenience and immediate gratification often overshadow various other considerations, including environmental concerns. Understanding these trends is significant in addressing the pressing issue of food waste. This research provides valuable data and information for creating strategies aimed at reducing food waste in both urban and rural areas. In addition, cultural preservation is indicated as lacking especially in urban areas, underscoring the need to balance modern convenience with the preservation of cultural heritage. The findings of this research are not limited to South Korea, but have broader relevance in the global fight against food waste. Urbanization is a global phenomenon, and as cities expand, the patterns observed in South Korea are mirrored in urban centers worldwide. To gain a more extensive understanding of consumer behavior and its effects on food waste generation, I plan to begin interviews with a more diverse population in Korea. With this, I hope my research will be valuable for individuals in realizing the change in their own behavior, and for larger groups of people and organizations to take action against food waste.

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Biological Implications of Human Space Exploration: Microgravity and Radiation Dysregulated Genes

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Abstract

The future of crewed human space exploration shows great potential, as plans for long-term settlements on the Moon, and future missions to Mars are being planned. However, our understanding of the biological effects of long-term space travel on humans is largely underdeveloped.

To understand the biological effects of microgravity and radiation experienced during space travel, the National Aeronautics Space Administration (NASA) GeneLab database was used to find differential expression data from different datasets that explored the conditions of *microgravity v 1g* and *10cGy v 1cGy* (where cGy is centigray, a measure of radiation). Next, commonly dysregulated genes were found in the microgravity sets and radiation sets, and then compared to find common dysregulated genes among both conditions. Using the Expression Atlas database, the dysregulation of these genes could be associated with human disease. HSBP1 and FTH1 were commonly dysregulated under microgravity, and MBNL2, LRMP, KDM3A, MPHOSP8, CSNK2B, and INTS3 were commonly dysregulated under both conditions of radiation and microgravity.

The two genes commonly dysregulated under microgravity, HSBP1 and FTH1, were widely associated with tumor growth and were also associated with central nervous system (CNS)-related complications like Alzheimer's when downregulated. In the other six genes, five were widely associated with tumor risk, most commonly in the breast, lung, and CNS, and five suggested that space travel as a whole could increase tumor risk. Seven of the eight genes were associated with breast and either CNS-related tumors or CNS-related complications like Aicardi-Goutières syndrome or Alzheimer's. In addition, both common microgravity genes and five of the six common genes across both conditions were inconsistently dysregulated among sets, which could suggest that they had a diverse influence with biological effects in many places of the human body.

1. Introduction

Ever since the first dog was launched into space in 1957, the understanding and development of space travel has greatly advanced. As a new age of space travel is being entered, organizations like NASA, the European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA) are providing resources to advance space-related systems. Often, these advances are translated for use on Earth to advance the interdisciplinary scientific development of humanity.[1] For example, technologies developed by these agencies led to the advancement of pacemakers, DNA damage detection, image-analysis software for tumors, artificial limbs, camera phones, and more.[2] However, to advance the understanding of science in a safe manner through space travel, the maintenance of astronaut health in space is of the utmost importance. While other factors like isolation and nutrition can affect human health in space, this study will focus on the effect that microgravity and radiation have on human health.

1.1. Radiation

While missions in low-Earth orbit like the International Space Station (ISS) are protected by the Earth's magnetosphere, upcoming missions to the Moon and beyond (like the NASA Artemis missions) will experience considerably higher radiation exposure.[3] Radiation in space comprise galactic cosmic rays (GCRs) (high-energy protons and ions from interstellar space), protons from solar particle events (SPEs), and particles trapped within the planet's own magnetosphere. As an astronaut leaves the Earth's atmosphere, their susceptibility to GCRs and SPEs will increase greatly. GCRs are composed of high charge and energy ions (HZEs) (1%), protons (85%), positrons (2%), and helium nuclei (12%). However, SPEs are composed of low-energy to medium-energy protons.[4] Although damage from SPEs can be prevented with spacecraft shielding, protection from GCRs (eg. HZEs) is particularly difficult due to their highly ionizing nature. This increased exposure can be tested on current missions in orbit and future ones to the Moon and Mars. More specifically, radiation exposure is estimated to be 0.3 cGy yearly on Earth, 3-12 cGy yearly on ISS missions, 10-12 cGy yearly on lunar missions, and over 30-45cGy on a 3-year mission to Mars.[5] Furthermore, radiation exposure is highly dependent on solar activity: when solar activity is high, it diverts GCRs, resulting in low GCR exposure and high SPE exposure, and when solar activity is low, GCR exposure is high and SPE exposure is low.

Radiation is also widely accepted to be a physical carcinogen and is a significant driver for tumor risk and for detrimental CNS effects through DNA damage. According to the NRC, above a dose of 10cGy, a firm link can be established between radiation exposure and cancerous growth.[6] Although HZEs make up a small proportion of total GCRs, their negative biological effects are disproportionately higher: they can cause complex single-strand and double-strand DNA breaks that are difficult to repair, and are associated with cancer, cardiovascular disease, and neurodegenerative complications.

1.2. Microgravity

Since the development of the first unicellular organisms, life on Earth has evolved to an environment with constant gravity. However, space travel involves a large spectrum of this force that varies from the constant value of gravity on the surface of the Earth (G): 1/6th G on the Moon, 1/3rd G on Mars, 3-6G during landing and

launch, ~0G in free space. It is known that microgravity can cause fluids like blood to shift towards the head and away from the lower body, leading to decreased leg volume. Additionally, because bones no longer experience gravitational unloading under microgravity, this can cause them to weaken. The effects of microgravity on the immune system are diverse and were first predicted for the Gemini missions and observed in the Apollo missions where astronauts suffered from bacterial and viral infection. As well as this, in a landmark 30-year-old study, lymphocytes experienced only 3% activation in microgravity conditions when compared with 1G.[7] However, this requires further research, and the biological effects of microgravity are much less understood than those of radiation.

1.3. The Future of Space Travel and Astronaut Health

The crewed NASA Artemis Missions to the Moon begin as soon as 2024, and soon after, humanity will begin crewed missions to Mars.[3] While the Apollo missions give some data on the dangers of space-travel in the short-term on the lunar surface, the Artemis missions aim to create long-term settlements on the Moon, where exposure to radiation will increase and the duration spent in microgravity by astronauts will be elongated greatly. Earth's magnetosphere has kept ISS astronauts safe from large amounts of ionizing radiation since the station's inception, but this new era of space travel creates the need for more research into the effects of long-term low dose ionizing radiation and microgravity specifically. If an understanding of the biological effects of space travel is developed, astronauts can be protected and achieve the long-term goals of extra-planetary inhabitation without significant health risks or disasters.

Currently, the biological effects of long-term space travel, specifically in the condition of microgravity, are poorly understood. Therefore, the aim of this paper is to use the NASA GeneLab and the Expression Atlas databases to find how ionizing radiation and microgravity can affect human gene expression and human health, so that solutions can be found to advance long-term space travel. Specifically, the hypothesis is that the conditions of space will increase the risk of tumors and other diseases. Microgravity will increase risk as it is an unnatural environment for humans who have evolved in the presence of gravity for centuries, and radiation will increase risk as it can damage DNA and cause mutations due to its high energy. Furthering the understanding of these biological effects can advance space-travel by protecting the health of human astronauts.
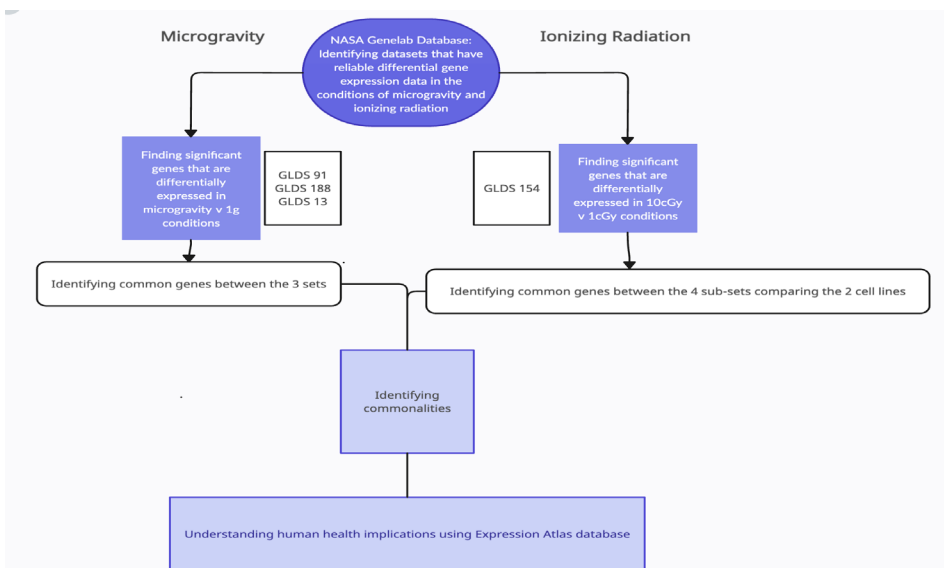
2. Methodology

The NASA GeneLab database is a space-related omics database that contains data pertaining to biological experiments that are relevant to spaceflight.[8,9] To understand how ionizing radiation and microgravity can affect human gene expression the differential expression analyses of different datasets in the database were used, each of which are connected to a research study. Later, to understand how this dysregulation affected human health, The Expression Atlas, a database that provides information on gene expression patterns and how they relate to complications, was used, as seen in Figure 1.[10]

These two conditions, microgravity and ionizing radiation, were observed across multiple differential expression datasets on GeneLab to identify which sets had significant data for the dysregulation of genes. There were three microgravity datasets and one ionizing radiation dataset that could be applied for this experiment, as listed

in Table 1. Next, the common genes in the condition of microgravity and the common genes under the exposure of ionizing radiation were again compared to find the common dysregulated genes between the two conditions. To understand their implications for human health, the Expression Atlas database was used.

Table 1. *The datasets used from the NASA GeneLab database, including information on the cell type and nature of the conditions in the experiment.*

Ionizing Radiation	Microgravity
	GLDS 188[12]: Jurkat T lymphocytic cells (in-flight)
GLDS 154[11]: lymphoblastoid cells	GLDS 13[13]: Activated T cells (onboard ISS)
	GLDS 91[14]: TK6 lymphoblastoid cells (simulated microgravity)

Figure 1. *An overview of the methodology followed to collect and analyze the gene expression data.*

2.1. Identifying genes dysregulated by microgravity

To identify microgravity's effect on gene expression, the datasets GLDS 188, GLDS 13, and GLDS 91 were used on NASA's GeneLab database. On each of these databases, the comparison *microgravity v 1g* or its equivalent was considered in the three differential expression datasets. Next, all p-values above 0.05 were filtered out to only consider significant results. By using Venny, a Venn diagram software for large datasets, the genes from each of these three datasets could be compared in a diagram format to easily understand which were common.[15]
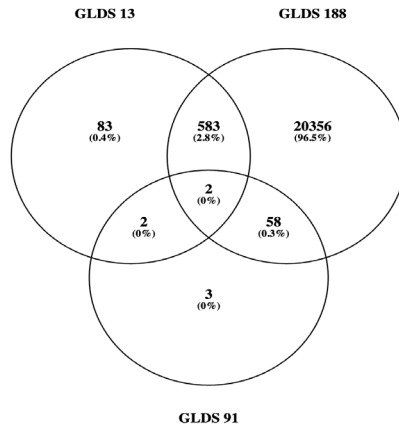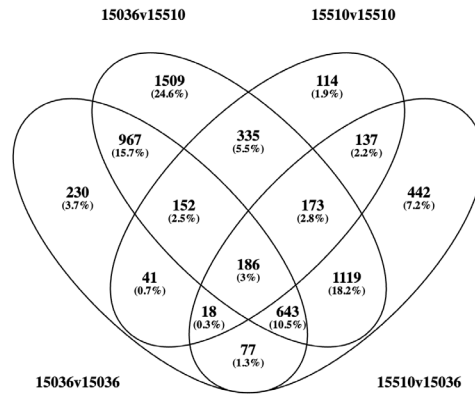
Figure 2. *Compares the significant dysregulated genes in three microgravity datasets (GLDS 13, GLDS 188, GLDS 91) using Venny. 585 common genes found between GLDS 13 and GLDS 188. 2 common genes found among all three sets.*

2.2. Identifying genes dysregulated by ionizing radiation

To identify radiation's effect on gene expression, the dataset GLDS 154 was used on NASA's GeneLab database. On this dataset, the comparison *10cGy v 1cGy* was considered (where cGy represents centigray). As this dataset includes differential expression analysis for 2 lymphoblastoid cell lines (15036 and 15510), a total of four sub-datasets were utilized from GLDS 154: *15510v15510, 15036v15036, 15510v15036,* and *15036v15510*. Next, all p-values above 0.05 were filtered out to only consider significant results. Genes from each of these four sub-datasets were compared using Venny.

The GLDS 154 dataset also contained data for the comparisons *7.5 cGy v 1cGy, 5cGy v 1cGy, and 2.5cGy v 1cGy,* representing different variation comparisons in radiation exposure. These were not considered in this experiment for two reasons. One, when all dysregulated genes from these sets were also added to the same diagram, no commonalities in dysregulated genes were found. Two, the highest variation (10cGy) was considered in this experiment to reflect long-term space travel's higher levels of exposure. While long-term space travel will surely have ionizing radiation exposure levels above 10cGy, these data was the only reliable data set available and will still accurately measure low dose ionizing radiation's effect on gene expression.
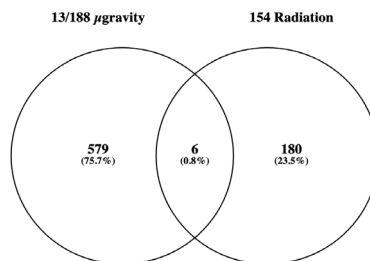
Figure 3. *Compares the significant dys-regulated genes in the radiation dataset between the 2 cell lines (GM 15036 and GM 15510) using Venny. 186 common genes found.*

2.3. Identifying the commonly dysregulated genes due to the conditions of microgravity and ionizing radiation

The 585 common genes between GLDS 13 and GLDS 188 were compared with the 186 common genes among the 4 sub-datasets in GLDS 154.

The GLDS 91 set was not considered in microgravity due to its limited data points with p-values below 0.05. This set's limited commonalities may have also been due to its different cell type from the other two microgravity sets, as it analyzed lymphoblastoid cells instead of T-cells.

Figure 4. *Compares the common significant dysregulated genes between the comparison of 1) Microgravity: GLDS 13 and GLDS 188 and 2) Radiation: GLDS 154. 6 common genes found.*

### 2.4. Understanding the implications on human health using Expression Atlas

After collecting gene expression data, as well as the common dysregulated genes in microgravity, radiation, and among both, the Expression Atlas was used to associate this dysregulation with diseases. By selecting 'disease' or 'disease staging,' the specific diseases associated with dysregulation were identified, which also provided information regarding what the gene's role in the body may be (i.e. tumor suppressor or promoter). After collecting a list of diseases each gene was associated with from the database, these lists were compared against each other to understand how frequently each complication was associated with these genes.[16] That way, a more complete understanding of how likely a specific complication could increase in risk during space travel can be developed. This comparison can help identify which diseases were common across all the identified common genes, as well as microgravity genes specifically to further understand its effect on human health.

3. Results

The collected data is of two types and from two sources: differential gene expression data from NASA GeneLab and disease-related data from the Expression Atlas. Differential gene expression data is presented in two ways in this paper, via heat maps and tables. First, the tables present log 2-fold changes that represent the logarithmic change in gene expression from one condition to the other. For the condition of microgravity, the datasets compared "*microgravity v earth gravity*" or "*μg v 1g.*" This means the data values represent the log 2-fold change of a gene being dysregulated under the condition of microgravity from a gene being dysregulated under the condition of earth gravity. Similarly, for the condition of radiation, the datasets compared "*10cGy v 1cGy,*" so the data values represent the log 2-fold change of a gene being dysregulated under the condition of 10cGy from a gene being dysregulated under the condition of 1cGy. Logarithmic comparisons with the base 2 were used because they provide data values that can be conveniently analyzed. Second, heat maps present the same information of log 2-fold changes but using color coding, where red signifies upregulation and blue signifies downregulation of a gene. The second type of data was disease-related data from the Expression Atlas, which is presented in the form of a table with a list of relevant diseases connected to the associated dysregulation.

3.1. Common Genes in Microgravity Sets (GLDS 91, GLDS 13, GLDS 188)

In this section, information related to the 2 genes that were found to be common across all 3 microgravity sets, HSBP1 and FTH1, is presented.
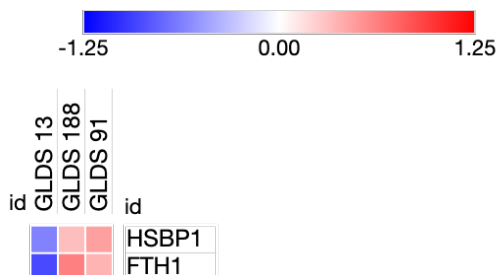
Figure 5. *A heatmap visualizing the log 2-fold expression changes of the two common genes across the three microgravity datasets (GLDS 91, GLDS 13, GLDS 188).*

HSBP1

Table 2. *Dysregulation data for HSBP1 in 3 microgravity sets.*

GLDS 13 (μg v 1g)		GLDS 188 (μg v 1g)		GLDS 91 (μg v 1g)	
log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value
-0.61	0.0078	0.32	1.30E-03	0.47	3.30E-03

HSBP1 is a gene that is responsible for the heat-shock response, in which mutations are also associated with neurodegenerative complications.[17,18] The data reveal that HSBP1 is downregulated in GLDS13, but consistently upregulated in both GLDS 188 and GLS91.

Data from the Expression Atlas reveals that HSBP1 is associated with tumor growth throughout the body when upregulated and downregulated, although it has other esophageal and nervous-system related complications when downregulated specifically.

Table 3. *An overview of the diseases HSBP1 is connected to when dysregulated according to the Expression Atlas database.*

Upregulation	Downregulation
- Ductal carcinoma - Ependymoma - Pancreatic adenocarcinoma - Ovarian cancer - Pneumonia - Eczema	- Diabetic nephropathy - Psoriasis - Alzheimer's - Renal, esophageal adenocarcinomas - Barrett's esophagus - Ataxia Telangiectasia - Leukemia - Ovarian cancer

FTH1

Table 4. *Dysregulation data for FTH1 in 3 microgravity sets.*

GLDS 13 (μg v 1g)		GLDS 188 (μg v 1g)		GLDS 91 (μg v 1g)	
log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value
-0.89	0.048	0.62	5.50E-10	0.37	0.00099

FTH1 is a gene that is responsible for encoding the heavy subunit of ferritin, a major protein associated with intracellular iron storage. In addition, defects in these proteins have often been linked to neurodegenerative diseases.[19] According to the data, FTH1 is downregulated in GLDS 13, but consistently upregulated in GLDS 188 and GLDS 91.

According to the Expression Atlas, FTH1 is linked to a heightened risk of tumors in many organs of the body when both upregulated and downregulated. However, when downregulated, the gene is associated with a high frequency of CNS-related complications.

Table 5. *An overview of the diseases FTH1 is connected to when dysregulated according to the Expression Atlas database.*

Upregulation	Downregulation
- Lung, colorectal carcinomas - Macroglobulinemia - Multiple sclerosis - Subependymal giant cell astrocytoma - Myeloma - Dermatomyositis - Pancreatic adenocarcinoma - Macrophage activation syndrome - Psoriasis - Arthritis	- Neuroectodermal, teratoid tumors - Colon, lung, esophageal adenocarcinomas - Gastric, Hepatocellular carcinomas - Gastric, breast cancers - Medulloblastoma - Ependymoma - Multiple sclerosis - Alzheimer's - Myelodysplastic syndrome - Melanoma - Barrett's esophagus - Leukemia - Mesothelioma - Aicardi-Goutières syndrome - Erythroleukemia - Myxosarcoma

3.2. Common Genes in Microgravity & Radiation Sets (GLDS 188, GLDS 13, GLDS 154)

In this section, information related to the 6 genes that were found to be common across all 3 sets, MBNL2, LRMP, KDM3A, MPHOSPH8, CSNK2B and INTS3, is presented.
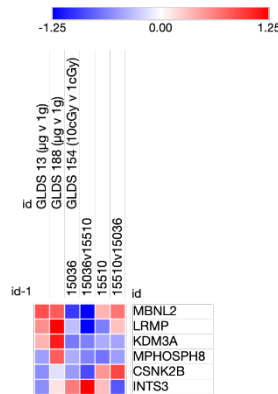
Figure 6. *A heatmap visualizing the log 2-fold expression changes of the 6 common genes among the two microgravity datasets (GLDS 13, GLDS188) and the radiation dataset (GLDS 154).*

MBNL2

Table 6. *Dysregulation data for MBNL2 in 2 microgravity sets and 4 radiation sets.*

GLDS 13 (µg v 1g)		GLDS 188 (µg v 1g)		GLDS 154 (10cGy v 1cGy)							
				15036v15036		15036v15510		15510v15510		15510v15036	
log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value
0.86	0.021	0.8	2.00E-10	-0.97	1.60 E-07	-1.3	3.90 E-11	0.37	0.02	0.68	1.50 E-05

MBNL2 is a gene that is responsible for mediating alternative splicing of mRNA, mainly in the muscles.[20] The data demonstrate that MBNL2 is consistently upregulated in *microgravity v 1g* conditions, but inconsistently upregulated and downregulated in *10cGy v 1cGy* radiation levels among individuals. While the gene is downregulated in cell line 15036 and in comparing 15036v15510, it is upregulated in 15510 and in comparing 15510v15046.

The data from the Expression Atlas demonstrate that both downregulation and upregulation of this gene are associated with tumor growth, although its prevalence is significantly higher during downregulation. In addition, it is worth noting that downregulation causes a high frequency of CNS-related tumors.

Table 7. *An overview of the diseases MBNL2 is connected to when dysregulated according to the Expression Atlas database.*

Upregulation	Downregulation
- COVID-19 in colon - Ejaculatory azoospermia - Aicardi-Goutières syndrome - Leukemia	- Lung, colon, renal adenocarcinomas - Lung, breast cancers - Sonic hedgehog medulloblastoma - Glioblastoma multiforme - Colitis - Leukemia - Septic shock - Tuberculosis - Uterine leiomyosarcoma - Astrocytoma - Ependymoma - Teratozoospermia - Neuroectodermal tumor

LRMP

LRMP, which is also called IRAG2, is a gene that is expressed in a developmentally regulated manner in lymphoid tissue, and plays a role in the delivery of peptides, maintaining nuclear shape, and more.[21] According to this data, LRMP is consistently upregulated in *microgravity v 1g* conditions, but inconsistently upregulated and downregulated in *10cGy v 1cGy* radiation levels among individuals, although a majority, 3 of 4 sets, are downregulated. While the gene is downregulated in cell line 15036, in comparing 15036v15510 and in cell line 15510, it is upregulated in comparing 15510v15046.

According to Expression Atlas, both the upregulation and downregulation of this gene are associated with tumor growth and cancer, while downregulation alone is associated with glioma, various other cancers, and arthritis. Also, it is worth noting that, according to the database, upregulation is associated with leukemias at a high frequency.

Table 8. *Dysregulation data for LRMP in 2 microgravity sets and 4 radiation sets.*

GLDS 13 (µg v 1g)		GLDS 188 (µg v 1g)		GLDS 154 (10cGy v 1cGy)							
				15036v15036		15036v15510		15510v15510		15510v15036	
log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value
0.55	0.013	1.5	7.50 E-17	-0.31	0.0076	-1.3	3.90 E-13	-0.64	6.60 E-06	0.3	0.0076

Table 9. *An overview of the diseases LRMP is connected to when dysregulated according to the Expression Atlas database.*

Upregulation	Downregulation
- Adenocarcinoma - Neoplasm - Chronic lymphocytic, Promyelocytic, Chronic myelogenous leukemias - Pancreatic ductal adenocarcinoma neoplasm - Gastritis - Colitis	- Chronic myelogenous leukemia - Dysplasia - Ulcerative colitis - Glioma - Colon adenocarcinoma - Psoriatic arthritis - Pancreatic, colon, lung cancers - Neoplasm

KDM3A

Table 10. *Dysregulation data for KDM3A in 2 microgravity sets and 4 radiation sets.*

GLDS 13 (µg v 1g)		GLDS 188 (µg v 1g)		GLDS 154 (10cGy v 1cGy)							
				15036v15036		15036v15510		15510v15510		15510v15036	
log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value
0.37	0.04	1.1	9.20 E-13	-0.66	6.80 E-05	-0.62	2.90 E-05	-0.41	0.015	-0.44	0.0034

KDM3A is a gene that is responsible for various processes including androgen receptor signaling pathway, formaldehyde biosynthetic process, and histone H3-K9 demethylation, and is also associated with various cancers.[22] The data demonstrate that KDM3A is consistently upregulated in *microgravity v 1g* conditions and is consistently downregulated in *10cGy v 1cGy* radiation levels across both cell lines.

According to the Expression Atlas, both upregulation and downregulation of this gene were associated with tumor growth, although upregulation alone is

associated with a larger proportion and variation of carcinomas and tumors including CNS-related tumors, while downregulation alone is associated with osteoarthritis, Alzheimer's, and azoospermia.

Table 11. *An overview of the diseases KDM3A is connected to when dysregulated according to the Expression Atlas database.*

Upregulation	Downregulation
● Colon, prostate, lung adenocarcinomas ● Oligodendroglioma ● Glioblastoma ● Renal cell carcinoma ● Biliary atresia ● Astrocytoma ● Glioblastoma multiforme ● Dermatomyositis	● Lung carcinoma ● Osteoarthritis ● Colon adenocarcinoma ● Breast, ovarian cancers ● Melanoma

MPHOSPH8

Table 12. *Dysregulation data for MPHOSPH8 in 2 microgravity sets and 4 radiation sets.*

GLDS 13 (µg v 1g)		GLDS 188 (µg v 1g)		GLDS 154 (10cGy v 1cGy)							
				15036v15036		15036v15510		15510v15510		15510v15036	
log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value
-0.48	0.049	0.8	2.10 E-16	-0.4	0.0025	-0.61	3.10 E-06	-0.69	1.00 E-05	-0.48	2.70 E-04

MPHOSPH8 is a gene that is responsible for chromatin binding activity and methylated histone binding activity.[23] This gene is also observed to promote cancer growth and metastasis through the promotion of cell proliferation.[24] According to the data, MPHOSPH8 is inconsistently upregulated and downregulated in the two *microgravity v 1g* sets, while it is consistently downregulated under *10cGy v 1cGy* radiation conditions.

The data from the Expression Atlas suggest that both upregulation and downregulation are associated with tumor growth, although the association is more evident during downregulation, whereas upregulation is uniquely associated with a muscle weakening disease, Acute Quadriplegic Myopathy.

Table 13. *An overview of the diseases MPHOSPH8 is connected to when dysregulated according to the Expression Atlas database.*

Upregulation	Downregulation
● Acute Quadriplegic Myopathy (AQM) ● Intraductal papillary-mucinous adenoma ● Mesothelioma	● Invasive ductal carcinoma ● Lung adenocarcinoma ● Renal adenocarcinoma ● Glioma ● Glioblastomas ● Ovarian cancer ● Osteosarcoma ● Hepatobiliary carcinoma ● Pancreatic adenocarcinoma ● Colorectal adenocarcinoma ● Breast carcinoma

CSNK2B

Table 14. *Dysregulation data for CSNK2B in 2 microgravity sets and 4 radiation sets.*

GLDS 13 (μg v 1g)		GLDS 188 (μg v 1g)		GLDS 154 (10cGy v 1cGy)							
				15036v15036		15036v15510		15510v15510		15510v15036	
log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value
-0.56	0.016	-0.15	9.9 E-04	-0.5	0.0044	-0.89	6.60 E-07	0.52	0.0058	0.91	2.10 E-06

CSNK2B is a gene that is responsible for regulating metabolic pathways, signal transduction, transcription, translation, and replication.[25] The data reveal that CSNK2B is consistently downregulated in *microgravity v 1g* conditions, while it is inconsistently downregulated and upregulated in *10cGy v 1cGy* radiation conditions. While the gene is downregulated in the 15036 cell line and in comparing 15036v15510, it is upregulated in the 15510 cell line and in comparing 15510v15036.

According to the Expression Atlas, dysregulation of this gene does not predominantly affect tumor growth, but rather other varied complications across different organs. According to the database, the dysregulation of this gene was additionally associated with Crohn's disease in both downregulation and upregulation.

Table 15. *An overview of the diseases CSNK2B is connected to when dysregulated according to the Expression Atlas database.*

Upregulation	Downregulation
● NLRC4-Macrophage Activation Syndrome ● Sebaceous of Jadassohn nevus ● Arthritis ● Crohn's disease	● Chronic kidney disease ● Crohn's disease ● Breast carcinoma ● Breast cancer

INTS3

Table 16. *Dysregulation data for INTS3 in 2 microgravity sets and 4 radiation sets.*

GLDS 13 (μg v 1g)		GLDS 188 (μg v 1g)		GLDS 154 (10cGy v 1cGy)							
				15036v15036		15036v15510		15510v15510		15510v15036	
log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value	log 2-fold change	adj. p-value
-0.56	0.012	0.14	0.0013	0.65	3.50 E-05	1.8	1.80 E-14	0.32	0.044	-0.83	5.50 E-07

INTS3 is a gene that is responsible for mediating genome stability through DNA damage response.[26] According to the data, the dysregulation of INTS3 is

inconsistently upregulated and downregulated in *microgravity v 1g* conditions and *10cGy v 1cGy* radiation conditions.

Data from the Expression Atlas demonstrate that downregulation specifically is associated with arthritis and many tumors throughout the body, while upregulation is associated with melanoma alone.

Table 17. *An overview of the diseases INTS3 is connected to when dysregulated according to the Expression Atlas database.*

Upregulation	Downregulation
● Melanoma	● Arthritis
	● Hepatobiliary carcinoma
	● Glioblastoma
	● Metastatic melanoma
	● Lung carcinoma
	● Pancreatic adenocarcinoma
	● Breast carcinoma
	● Colorectal adenocarcinoma

3.3. Analysis of the Expression Atlas disease data

To understand the prevalence of a disease being associated with each of these genes, they were compared with each other to find the commonly associated diseases with these genes.

Microgravity & Radiation (6 common genes)
Lung tumors: 5 of 6 (INTS3 KDM3A LRMP MBNL2 MPHOSPH8)
CNS-related tumors: 5 of 6 (INTS3 KDM3A LRMP MBNL2 MPHOSPH8)
Breast tumors: 5 of 6 (CSNK2B INTS3 KDM3A MBNL2 MPHOSPH8)
Colon tumors: 3 of 6 (KDM3A LRMP MBNL2)
Pancreatic tumors: 3 of 6 (INTS3 LRMP MPHOSPH8)
Arthritis: 3 of 6 (CSNK2B INTS3 LRMP)
Colitis: 2 of 6 (LRMP MBNL2)
Leukemia: 2 of 6 (LRMP MBNL2)
Renal tumors: 2 of 6 (MBNL2 MPHOSPH8)
Ovarian tumors: 2 of 6 (KDM3A MPHOSPH8)
Melanoma: 2 of 6 (INTS3 KDM3A)
Hepatobiliary tumors: 2 of 6 (INTS3 MPHOSPH8)
Colorectal tumors: 2 of 6 (INTS3 MPHOSPH8)

Microgravity (2 common genes HSPB1 and FTH1)
Common complications: Breast tumors, CNS tumors, Pancreatic tumors, Psoriasis, Alzheimer's, Esophageal tumors, Barrett's esophagus, and Leukemia.

Below are some of the generalizations when the data was being compared.
Breast tumors: Breast and ductal tumors
CNS tumors: Ependymoma, Macroglobulinemia, Subependymal giant cell astrocytoma, Neuroectodermal tumor, Teratoid tumor, Medulloblastoma, Sonic hedgehog medulloblastoma, Glioblastoma multiforme, Astrocytoma, Glioma, Oligodendroglioma, Glioblastoma

4. Discussion

In the majority of the above studied genes, microgravity and radiation increased disease risk, most commonly tumor growth and CNS-related complications. While conclusions support the original hypothesis, there were some anomalies that must be met with further research.

First, for the two common microgravity genes studied (HSBP1 and FTH1), GLDS 188 and GLDS 91 experimental conditions consistently upregulated these genes while the experimental conditions of GLDS 13 consistently downregulated them. As all three sets were studying microgravity, this inconsistency could have stemmed from the different experimental conditions of GLDS 13 which was carried out on the ISS. On the ISS, the cells were likely exposed to higher radiation levels, while GLDS 188 and GLDS 91 were carried out on Earth, with lower radiation exposure levels. For both HSBP1 and FTH1, the dysregulation data suggested that microgravity is primarily associated with tumor growth, but also esophageal complications when downregulated and skin conditions like psoriasis and CNS-related complications when both downregulated and upregulated. The possible connection between HSBP1 and tumor growth can also be justified by the gene's purpose, which is to promote/induce? the heat-shock response, an indicator of cellular or oxidative stress. As the growth of a tumor would also signal cellular or oxidative stress, it is likely this gene would be dysregulated during tumor growth.

For the six common genes across microgravity and radiation (MBNL2, LRMP, KDM3A, MPHOSP8, CSNK2B, INTS3), many inconsistencies were present that were consistent with the hypothesis that microgravity and radiation could increase disease risk. These inconsistencies among datasets indicate the importance for personalized medical screening and treatment. Specifically, five of the six genes, MBNL2, LRMP, MPHOSPH8, CSNK2B, and INTS3 were inconsistently upregulated and downregulated within the conditions of radiation or microgravity, or both, and therefore could have multidirectional influences in the body. On the other hand, the consistent regulation of KDM3A could signify a consistent role in the body and among individuals as well. Overall, the dysregulation of all these genes could impact the body universally as opposed to resulting in a localized effect, as the complete list of complications they were associated with according to the Expression Atlas was never localized to one organ or system.

According to the Expression Atlas, MBNL2 is associated with tumors throughout the body when down regulated specifically, and hence could possibly be a tumor suppressor. For that reason, microgravity's upregulation of the gene most likely has a lower significance on tumor risk than radiation's downregulation of the gene. In addition, as this downregulation in radiation is dependent on the cell line (in some cell lines, or individuals, MBNL2 is upregulated), some may not be as susceptible to MBNL2 downregulation in radiation than others, and therefore not as susceptible to tumor risk. Moreover, radiation can have varied effects on different individuals in terms of its role in tumor risk. It is also worth noting that the high frequency of CNS-related tumors MBNL2 is associated with according to the Expression Atlas is justified by studies that indicate that the knockout of MBNL2 is associated with Myotonic Dystrophy, which can result in nervous system-related complications. [20,27,28,29]

For other genes, space travel in general, under the conditions of microgravity and radiation, always increased tumor risk, according to the collected data. The exception is CSNK2B. This gene was not explicitly linked to tumor growth like others, and while the data indicated that space travel altogether could increase the risk of Crohn's disease, it also indicated that radiation specifically could play a role with

arthritis, kidney issues, and skin issues, and microgravity specifically could play a role with kidney and breast issues. Aside from this, microgravity was also associated with a high frequency of leukemias in LRMP, while radiation was associated with other effects like osteoarthritis in KDM3A.

Lastly, while the effects of these genes were spread through the body, an analysis of the Expression Atlas database from Section 3.3 of the results suggests that lung, breast, and CNS-related tumors are most frequently associated with the six common genes, specifically 5 of the 6 genes, and are thus likely to be the most affected organs in the human body during manned space travel. However, arthritis and pancreatic and colon tumors were also common, associated with 3 of the 6 genes. In all, the conditions of space were seen to promote tumor risk throughout the human body, and were also associated with conditions like arthritis.

While many of the genes were primarily associated with tumor growth according to the Expression Atlas, oftentimes, diseases that were outliers to the others in that gene's associated diseases were identified, such as Macrophage Activation Syndrome (MAS) for FTH1, Acute Quadriplegic Myopathy (AQM) for MPHOSPH8, and azoospermia for MBNL2.

4.1. Limitations and future research

It must be noted that the cell lines used across all four experiments considered were varied, but may not be representative of gene expression throughout the whole human body due to their similarity as leukocytes. While GLDS 188 and GLDS 13 both used T-cells, GLDS 154 used two lymphoblastoid cell lines (GM 15036 and GM 15510), and GLDS 91 used TK6 lymphoblastoid cells. While these two main cell variants are both leukocytes, their expression values may not be directly comparable. However, comparing expressions across cell lines and types could be important for deducing the effect of space travel on humans across organs and individuals as opposed to just one cell line.

Although interpreting data on microgravity and radiation separately to create conclusions on space travel's effect on the human body can be effective, differences from realistic space exploration conditions can be present, and therefore the most important part of research going forward is to conduct detailed studies on the data available from astronauts during and after space missions. For instance, the unique form of ionizing radiation through GCRs could have a different composition when compared with the simulated radiation in experiments on Earth and the ones studied in this experiment, while microgravity may have widely different impacts when studied in the long term. In addition, short-term and long-term radiation exposure is known to have different impacts, and thus short-term simulated studies may have varied biological effects when compared with the long-term conditions of space. For this reason, human gene expression data must be collected for future missions to understand the collective effect of microgravity and space radiation, so that drugs or treatments can be identified to protect astronauts. Experiments must also be conducted simulating the conditions of space on Earth after collecting relevant data from future crewed space missions to compare data and identify the differences or similarities between simulated radiation from varied sources on Earth to galactic radiation to further understand its composition and biological effects.

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Using Molecular Dynamics Simulations to Explore the Diffusion of Diabetes Drugs Through Thermosensitive Materials Available for Microneedles

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Abstract

Diabetes, a well-known chronic metabolic disorder, has caused hyperglycemia and negatively affected the living quality of millions of people every year due to insulin secretion disorder. To avoid repetitive injections of insulin and improve patients' compliance, researchers have utilized thermosensitive materials to synthesize microneedles that are capable of on-demand delivery of insulin and other large molecule drugs. However, since currently available microneedles still cannot achieve sufficient drug release, there is a need to improve their drug-delivery performance and expand their use to a wider range of drugs. As relative studies reveal, thermosensitive microneedles are expected to have greater potential in disease treatment and improving the quality of human life.

Using the molecular dynamics simulation method, we have tested the diffusion effects of several popular small molecule and polypeptide diabetes drugs through poly(N-isopropylacrylamide), the most widely used thermosensitive polymer for drug delivery. The diabetes drug with the highest potential for release was identified by comparing the diffusion coefficients of well-known diabetes medications at temperatures below and above the polymer's lower critical solution temperature (LCST). The Materials Studio program is used to perform the diffusion simulation procedure.

Throughout the process, we have found that drug molecules with more hydrogen bond donors and acceptors, as well as those with more polar groups and fewer nonpolar groups, possess greater potential for application. Additionally, it has been demonstrated that small molecule drugs can be just as effective as polypeptides in terms of delivery capacity. The results could shed light on the future applications of small molecule drug delivery using microneedles, providing valuable experience for the future screening of small molecules within the fields of materials science and biomedical engineering.

1. Introduction

In recent years, diabetes has become one of the most prevalent chronic diseases worldwide, with the number of diabetic patients continuously rising. According to the International Diabetes Federation (IDF), there were approximately 536.6 million adults aged 20-79 with diabetes worldwide in 2021.[1] 90% of diabetes patients have type II diabetes, and clinical symptoms of type 2 diabetes patients are mainly manifested by insulin resistance (reduced sensitivity of target cells to the disruptive effect of insulin) and defects in pancreatic B cell function. Once diagnosed with diabetes, patients typically require lifelong medication and may even need to receive regular insulin injections to manage their condition.

Since the end of the last century, material science, as a branch of chemistry, has experienced rapid development. Due to the numerous ways in which monomers combine, polymers have a high degree of structural variability, and macromolecular materials have been proven to have diversified properties. Therefore, thermosensitive polymers have also received increasing attention from researchers because of their potential in drug delivery,[2, 3] selection of reactants[4] and molecular separation.[5] Among the reservoir of thermosensitive polymers, poly(N-isopropylacrylamide), also known as PNIPAM, is especially famous for its coil-to-globule transformation when experiencing a temperature elevation through its LCST (lower critical solution temperature), which is approximately 32°C.[6] The material is frequently utilized within the human body since its LCST is relatively close to the average human body temperature. When the external temperature is above the LCST of PNIPAM, hydrophobic interactions predominate, exposing alkyl groups and changing the overall conformation of the polymer from a coil to a globule. Below the LCST of PNIPAM, the hydrophilic amide groups are exposed to solvent water and form hydrogen ties with water molecules.[7] Therefore, PNIPAM has been proven to have a sufficient swelling capacity to 'squeeze out' drug molecules and rebuild structures according to temperature changes. Moreover, with the development of molecular dynamics simulation technology, researchers can now receive precise and energetically optimized simulation effects of molecular interaction and diffusion. This advance in technology further aids the applications of PNIPAM. However, although some studies have tried to investigate other materials that could aid the swelling capacity of PNIPAM,[8] and have used computational simulations to find out the most suitable monomer ratio (between N-isopropylacrylamide and other monomers commonly used for copolymerization to alter polymer LCST) for oral drug release,[9] they all focused on improvement of PNIPAM or using the material to promote solubility of less soluble oral drugs instead of application of PNIPAM or examination of suitable drug types for thermosensitive materials.
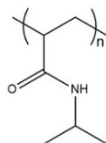
Figure 1. *Structure of poly(N-isopropylacrylamide) (tacticity not shown)*

In recent years, microneedles have also become a hot area of research due to their innovative and minimally invasive drug release capabilities.[10] The benefits of using microneedles as a therapeutic method include high safety, minimally invasive and painless treatment, low operational difficulty, and more precise drug release. Because of their great potential for minimizing the need for repetitive intravenous insulin injections and improving diabetic patients' life quality, several soluble microneedles have been

designed.[11] Being inspired by the problems and novelty of previous designs, researchers have used thermosensitive materials to synthesize microneedles that are capable of on-demand insulin release while optimizing their physical properties and biological efficacy. The synthesized thermosensitive microneedles have been tested to have the maximum swelling capacity, which is sufficient to penetrate the skin and shows great efficacy for in vitro and in vivo insulin release.[12] However, according to previous research, efforts to use a thermosensitive insulin-delivery microneedle for on-demand release of diabetes drugs have some discernable drawbacks, such as insufficient drug release.[12] The microneedles could only release a portion of the insulin loaded (slightly less than 50%), making it difficult to implement this novel method in industrial production and generate profits. This could be a result of insulin molecules' excessive size. Also, whether thermosensitive materials are able to improve the release of small molecule drugs is also unknown.

As new discoveries of small molecule drug treatments for Type II diabetes have been made in recent years, small molecules have the potential to enhance the efficacy of microneedles.[13, 14] Due to their molecular size, small molecule drugs may exhibit greater binding affinity with the needle body material and improved releasing capacity. Additionally, the increasing utilization of simulation methods in material science has enabled precise predictions of molecular diffusion through polymers under various conditions. To enhance the applicability and profitability of microneedles in industrial production and disease treatment, we have decided to employ computational simulations to examine the diffusion effects of several small molecule diabetes drugs through poly(N-isopropylacrylamide).

In this study, we selected several popular oral and intravenous small molecule drugs for diabetes treatment, along with a polypeptide drug and human insulin, and test their diffusion capacity under high and low temperatures through PNIPAM using molecular dynamics simulation. In this way, we could deduce the delivery effects of the chosen drugs within the environment of thermosensitive microneedles and therefore provide suggestions for further application of microneedles.

2. Methodology

Materials Studio from Biovia is a computer software widely used for materials modeling, especially for building polymer chains and mixture systems. It is also available for molecular dynamics simulation and allows for precise temperature control.[9, 15] Therefore, we use Materials Studio (2019) as our simulation platform. For drug choice, we select five drugs that have been proved effective for diabetes treatment, including Metformin, Dapagliflozin and Sitagliptin (all small molecule drugs, see Figure 2), Exenatide (pdb code 7mll),[16] and human insulin (pdb code 3i40) (Figure 3). The protein with pdb code 3i40, the gene-engineered human insulin, is chosen for insulin modeling to best imitate its application under an industrial setting.[17] To determine the drug delivery effects of different drugs quantitatively and precisely, we use molecular dynamics simulation for each molecule to imitate molecular motion within a cell that contains PNIPAM, a target drug and solvent (water). Each medicine is also evaluated at two different temperatures: one above the LCST of PNIPAM and one below it. Among functions provided by Materials Studio, Amorphous Cell tool is used for Model construction and property prediction for non-crystalline materials, particularly polymers, organic liquids, and their mixtures, while the Forcite tool is a collection of molecular mechanics tools, whose key approximation is that the potential energy surface on which the atomic nuclei move is represented by a classical forcefield. These characters indicate that Materials Studio possesses all necessary functions for conducting this experiment. Therefore, we use Amorphous Cell to construct a mixture environment of polymers and drugs, and Forcite to optimize cell energy, carry out molecular dynamics

simulation, and export the target molecule's mean square displacement (MSD) against time (t) curve.
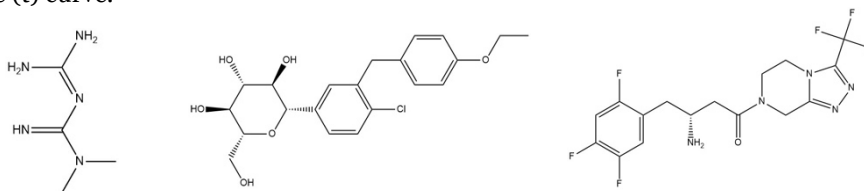
Figure 2. Chemical *Structures of Metformin, Dapagliflozin, and Sitagliptin*
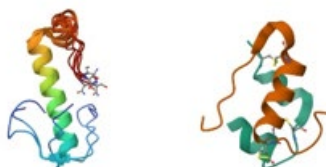
Figure 3. *Structures of Exenatide (pdb code 7mll) and Human Insulin (pdb code 3i40), adopted from https://www.rcsb.org/structure/7MLL and https://www.rcsb.org/structure/3I40*

Mean Squared Displacement (MSD) is a measure of the deviation between the instantaneous position and the initial position of a particle during its evolution over time.[18] It is obtained by recording the atomic positions of the first frame in the xyz file as the initial positions, then sequentially calculating the deviations between the atomic positions of all subsequent frames and the initial position, and eventually summing and averaging all deviations. MSD is related to molecules' diffusion coefficient, which is a parameter for the diffusion effect of molecules. According to Fick's First Law and Einstein's Principle Relation Formula, the relationship between MSD and the diffusion coefficient could be represented as the following[19, 20]:

$$D = \frac{a}{6}$$

Where D represents the diffusion coefficient (in terms of m²/s) and a refers to the slope of the straight line obtained by fitting the curve of MSD against time t.

Although diffusion coefficient only demonstrates the diffusion capacity of drug molecules under a specific temperature, comparing D for each of the drugs under different temperature conditions could illustrate drug delivery effectiveness under a thermosensitive microneedle environment because thermosensitive microneedles are made effective by allowing for a larger difference of diffusion capacity of drug molecules between high and low temperatures. For PNIPAM, the difference in diffusion capacity is made available by the difference in hydrogen bonding. PNIPAM exposes its hydrophilic groups at lower temperatures and creates additional hydrogen bonds with drug and water molecules. In contrast, hydrophobic groups dominate for temperatures above LCST, reducing PNIPAM's binding affinity with drug molecules and allowing molecules to diffuse.

Once we obtain all diffusion coefficients for each type of drug molecule under the two temperatures, we are able to analyze them in two ways. First, we could calculate the differences of a for each drug under different temperatures, which would demonstrate the variance of binding affinities between polymer material and drugs, and then the differences of a for all five drugs under the same temperature, which allow for analysis on overall diffusion capacity among all drugs. After determining the delivery

effectiveness of all drugs, further analysis of drug choice could be made.

3. Simulation Process

NIPAM monomer, water molecule, and drug molecules are first imported into Materials Studio through the sdf file from PubChem and the pdb file from rcsb.org. PNIPAM chain construction is then carried out with isotactic configuration and chain length 30 (Figure 4).
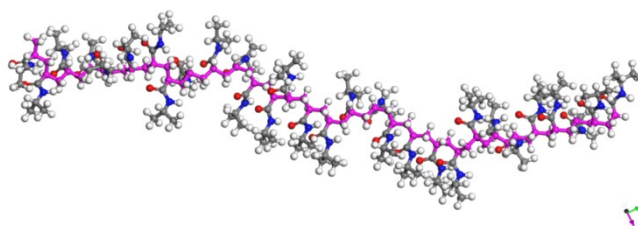

Figure 4. *PNIPAM chain visualization with isotactic configuration and chain length 30*

3.1. Amorphous Cell Construction and Packing

The first step is to construct a mixture of PNIPAM, target drug and water. Amorphous Cell is constructed by 'Construction' method with 5 chains of PNIPAM and 5 molecules of drugs under 298K (Lower temperature) or 330K (Higher temperature) with a density of $0.3g/cm^3$. Lattice type is set as 'cubic', and lengths of lattice, a, b, and c, are all automatically set. Visual presentation of construction is shown below. The structure of PNIPAM is 'stretched out' under 298K and crimples under 330K, as shown in Figure 5. Therefore, the construction produces a successful imitation of PNIPAM's structure in the real situation. After which, 'Packing' method is carried out to pack the cell with water molecules with a density of $0.7g/cm^3$ (Figure 6). Throughout the two processes, we use the COMPASS forcefield, a universal forcefield that is used in all-atom simulations of polymer, to calculate molecular interactions within the cell. Simulation quality is set at 'coarse' and energy is partially optimized through the process.
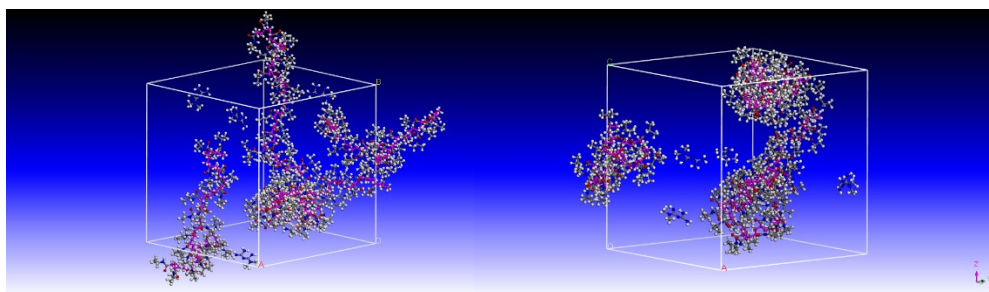
Figure 5. *Cell containing poly-NIPAm and Metformin under 298K (left) and 330K (right). The coil-to-globule change from lower to higher temperatures is readily visible in these arrangements.*
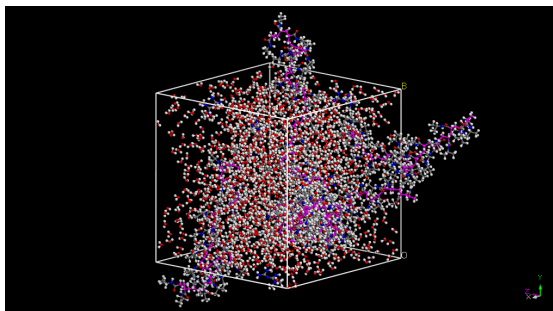
Figure 6. *Amorphous Cell constructed under 298K. The cell contains 5 PNIPAM chains, 5 Metformin molecules and water. The total density is set at 1g/cm³, and the density of water is 0.7g/cm³. Only the temperature and drug molecule are modified in the remaining cells, which are generated under identical circumstances.*

3.2. Geometry Optimization and Molecular Dynamics Simulation

The geometry optimization and simulation is carried out by Forcite tools. As the geometric position could affect the efficacy of molecular dynamics simulation, 'geometry optimization' is first operated to achieve an optimized geometric position of molecules with maximum iterations set at 500 times. This optimization is done to make sure we imitate the interaction between molecules accurately and minimize the 'terminal effect' of the polymer. Finally, the molecular motion of the mixture is simulated under 298K or 330K for a total simulation time of 5ps and time step 1fs, so there is a total of 5000 steps. Every 250 steps the system outputs a frame that shows the location of every molecule. The NVT ensemble is used throughout the operation to ensure that the parameters n of the atoms, v of the volume, and t of the temperature remain constant. After the simulation process finishes, we use the 'analysis' function to calculate MSD of all target drug in the cell within the first 9 frames.

4. Result, Analysis and Comparison

The results of the simulation are presented in the five graphs below. (Figure 7) (Original data included in Appendix). Through comparison of graphs, we can know that among the three small molecule drugs chosen, metformin has the highest difference in final MSD value, making it the most suitable drug for drug delivery under a thermosensitive microneedle environment. Its diffusion coefficient is also the largest among all drugs under 298K and 330K. Sitagliptin also has a relatively high difference in diffusion effect between high and low temperatures, which is larger than that of the two large molecule drugs, making it another ideal choice. However, Dapagliflozin does not appear to have a high difference in diffusion capacity between 298K and 330K.
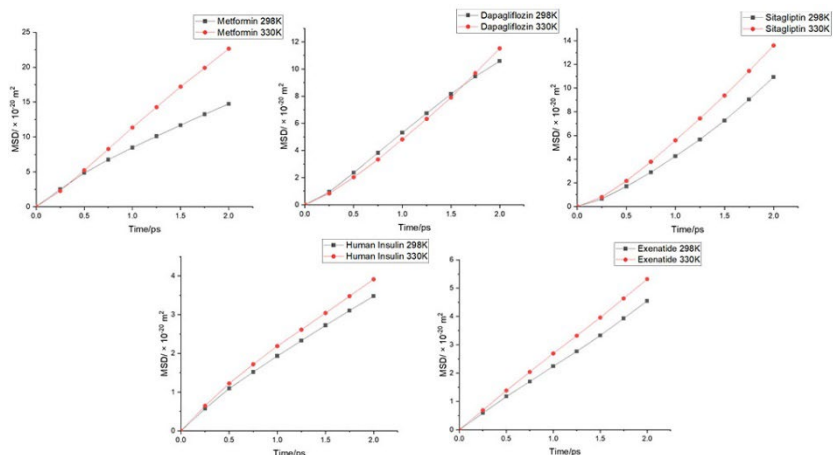
Figure 7. *Initial MSD data of the five drugs presented in five graphs, each with simulation conditions of 298K and 330K. A greater difference in the slope of the two lines shown in the graphs indicates a larger difference in diffusion capacity for the specific drug, which also implies that the drug could be an ideal choice for thermosensitive microneedle use.*
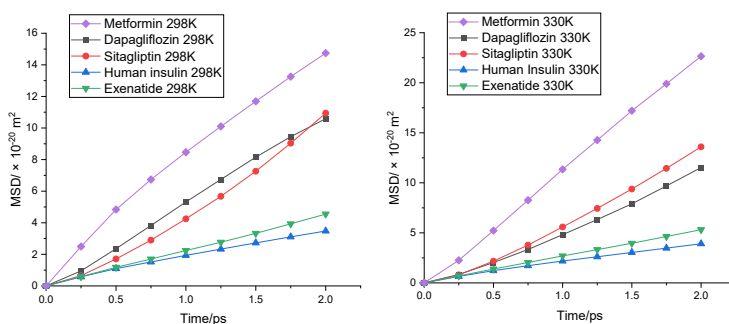
Figure 8. *Comparison of diffusion effect among all five drugs under the same temperature. The comparison could aid a structure-based explanation for diffusion capacity of different drugs above or under LCST of PNIPAM as small molecule drugs' relative diffusion capacity differs under the two temperatures, which could suggest that for small molecules, structural differences in organic groups, polarity, number of hydrogen bond donors and acceptors have a large impact on their delivery effect.*

Comparison of insulin's and exenatide's diffusion effects through PNIPAM reveals that exenatide, with a smaller molecular volume, has a higher diffusion coefficient under both 298K and 330K than human insulin has, which demonstrates exenatide's higher drug delivery capacity. However, for the two big molecules, the variation in diffusion between high and low temperatures is minor. This indicates that interactions between pharmaceuticals and polymers have less of an impact on the diffusion process of large molecule drugs, and these drugs may be less ideal for thermosensitive microneedle use than some small molecule drugs.

Quantitative presentation and analysis of diffusion coefficient are also presented below in Table 1. From the data, we can also conclude that Metformin

performs best among the five medicines because it has the greatest difference in diffusion coefficient between 298K and 330K. Also, Sitagliptin's difference is the second largest, which means it could perform well for thermosensitive response when loaded in a microneedle. Exenatide's performance is better than insulin. Additionally, its release rate is slower compared to the three small molecule drugs, so if loaded within thermosensitive microneedle, problems like excessive release are less likely to happen. Therefore, Metformin, Sitagliptin, and Exenatide are expected to have higher drug delivery performance than human insulin and further research could focus on these drugs to expand the application of thermosensitive microneedles.

Table 1. *Diffusion Coefficient of five selected drugs calculated based on previous data of MSD under 298K and 330K and their differences within each drug. A greater value in difference indicates a higher difference of diffusion effect under the two temperatures and means it has a larger potential in application.*

Diffusion Coefficient ($\times 10^{-20}$ m²/s)	Small molecule drugs			Large molecule drugs	
	Metformin	Dapagliflozin	Sitagliptin	Insulin	Exenatide
298K	1.20329	0.915085	0.92006	0.28414	0.37321
330K	1.92765	0.970915	1.15994	0.31850	0.43932
Difference	0.72436	0.05583	0.23988	0.03436	0.06610

Why some drug molecules have larger differences in diffusion coefficients than others is another important question, and understanding the question is crucial for generalizing the five drugs selected in this experiment to the diffusion effect prediction of all drugs. To account for the difference in diffusion capacity, we turn to determining the free volume within the PNIPAM cell. According to Fox and Flory's free volume theory, the volume of a polymer consists of two parts. One part is occupied by the molecular chains, known as the occupied volume. The other part is formed by the defects and voids resulting from the random packing of the molecular chains, known as the free volume.[21] The free volume, dispersed in the polymer as voids of varying sizes, provides space for chain segment movement and allows for the adjustment of conformation through rotation and displacement. At the same time, the diffusion behavior of molecules within the polymer is closely related to the size and shape of the free volume. In general, as the fraction of free volume rises, so does a polymer's diffusion coefficient.[22]

To obviate the influence of total cell volume, we use the concept of free volume fraction to measure the material's compaction under different temperatures. If p stands for the free volume fraction, V_o is for occupied volume within cell, and V_f is for free volume within cell, the relationship could be presented as follow:

$$p = \frac{V_f}{V_f + V_o} \times 100\%$$

We measure the value of p within a cell that only has 5 PNIPAM chains under each of the two temperatures, 298K and 330K. For each time, the probe radii are set to 1.25Å, 2.5Å, and 7.5Å, which creates a radius gradient that could be useful for studying the diffusion effect of drug molecules with different molecular dynamic radii.

The first step is to build up two cells with only five chains of PNIPAM in each cell under 298K and 330K. All parameters are identical to previous constructions. Then the occupied and free volumes of each cell are determined by each kind of probe radii.

Table 2. V_o, V_f and free volume fraction value of PNIPAM cell with different probe radii under 298K and 330K.

Temperature	Probe radii ($\times 10^{-10}$ m)	V_o ($\times 10^{-30}$ m^3)	V_f ($\times 10^{-30}$ m^3)	Free volume fraction
298K	1.25	32187.05	61822.37	65.762%
	2.5	45932.21	48077.21	51.141%
	7.5	85001.15	9008.26	9.582%
330K	1.25	29634.5	64374.92	68.477%
	2.5	42549.24	51460.17	54.739%
	7.5	83889.92	10119.49	10.764%

The data demonstrate that when the probe radii rise, fewer holes are present among interlacing polymer molecules, which causes the fraction of free volume to drop. These results explain the high diffusion coefficient of metformin molecules at different temperatures and the lower diffusion coefficient of two large molecular drugs as smaller drug molecules typically have smaller molecular dynamic radii and can pass through more holes in the polymer. Moreover, since under the same condition, free volume fraction under 330K is slightly higher than free volume fraction under 298K, the data give a reliable explanation of the better diffusion capacity of all drugs in the former experiment, except from the influence from temperature.

Apart from the explanation based on available volume within polymer cells, difference in the number of hydrogen bond donors or acceptors within drug molecules can account for the difference in diffusion capacity. Metformin has one acceptor and three donors for hydrogen bonds despite its modest molecular size. Also, metformin has only a few nonpolar groups (only two exposed methyl groups), allowing its higher binding affinity with PNIPAM under lower temperatures and lower binding affinity under higher temperatures. This is because PNIPAM has its polar groups, the amide groups, exposed under temperatures under its LCST, but mostly exposes its nonpolar groups under temperatures above its LCST. Similarly, we can tell the difference in diffusion capacity between dapagliflozin and sitagliptin. Dapagliflozin has 4 hydrogen bond donors and 6 acceptors, while sitagliptin has 1 donor and 10 acceptors. Additionally, dapagliflozin has more nonpolar carbon atoms than sitagliptin, which allows a higher resistance to diffuse away from PNIPAM under higher temperatures. Insulin's and exenatide's slower rate of diffusion is possibly caused by their relatively large size, making them hindered by PNIPAM. Also, under lower temperatures, the two drugs can hardly bind with polymer material through hydrogen bonds, leading to the small difference in their diffusion capacity between the two temperatures.

5. Conclusion

In summary, we have for the first time finished an all-atom molecular dynamics simulation of diabetes drug diffusion through PNIPAM material and provided powerful explanations for the difference in diffusion capabilities of the five drugs selected. We could now give the suggestion for future research and industrial application that drug molecules similar to metformin, sitagliptin, and exenatide could have greater potentials in delivery effect when loaded into thermosensitive materials.

However, one possible limitation is we did not apply a coarse-grained model and related force field, which would have better captured the thermosensitive property of polymer on the macro level due to computational device limitations.[23] Also, the results generated through the experiments above, although they might be significant to some extent, should not be considered as completely reliable until real experiments about diffusion are conducted. We suggest that researchers could focus on drug molecules that have more polar groups and fewer nonpolar groups and that have more hydrogen bond

donors and acceptors to find drug molecules that better fulfill the requirements of applying into thermosensitive microneedle treatment. Small molecular drugs could also have the potential for a better delivery capacity, but their intake dose for injection, unexpected toxicities, and other influencing factors should be considered.

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Appendix: Experimental Data (MSD Values in MD Simulation)

Table 1. *MSD values of Metformin under 298K and 330K*

Time(/ps)	MSD($\times10^{-20}$ m²/s)	Time(/ps)	MSD($\times10^{-20}$ m²/s)
0	0	0	0
0.25	2.894906	0.25	1.423074
0.5	6.066364	0.5	3.076744
0.75	9.39329	0.75	4.746263
1	12.71887	1	6.444441
1.25	16.04406	1.25	8.276297
1.5	19.3033	1.5	10.23988
1.75	22.20404	1.75	12.23365
2	25.02855	2	14.134

Table 2. *MSD values of Dapagliflozin under 298K and 330K*

Time(/ps)	MSD($\times10^{-20}$ m²/s)	Time(/ps)	MSD($\times10^{-20}$ m²/s)
0	0	0	0
0.25	0.949154	0.25	0.838847
0.5	2.360995	0.5	2.031358
0.75	3.827503	0.75	3.337509
1	5.314914	1	4.81873
1.25	6.739997	1.25	6.32859
1.5	8.15364	1.5	7.90334
1.75	9.450998	1.75	9.692995
2	10.58859	2	11.52121

Table 3. *MSD values of Sitagliptin under 298K and 330K*

Time(/ps)	MSD($\times10^{-20}$ m²/s)	Time(/ps)	MSD($\times10^{-20}$ m²/s)
0	0	0	0
0.25	0.650161	0.25	0.803418
0.5	1.705691	0.5	2.170743
0.75	2.897496	0.75	3.780366
1	4.24777	1	5.591505
1.25	5.672487	1.25	7.441476
1.5	7.26238	1.5	9.37781
1.75	9.035979	1.75	11.44611
2	10.93982	2	13.59771

Table 4. *MSD values of Human Insulin under 298K and 330K*

Time(/ps)	MSD($\times 10^{-20}$ m²/s)	Time(/ps)	MSD($\times 10^{-20}$ m²/s)
0	0	0	0
0.25	0.575965	0.25	0.647937
0.5	1.095308	0.5	1.223575
0.75	1.517562	0.75	1.717595
1	1.93258	1	2.188865
1.25	2.329482	1.25	2.611688
1.5	2.723652	1.5	3.041675
1.75	3.104854	1.75	3.47564
2	3.479284	2	3.912965

Table 5. *MSD values of Exenatide under 298K and 330K*

Time(/ps)	MSD($\times 10^{-20}$ m²/s)	Time(/ps)	MSD($\times 10^{-20}$ m²/s)
0	0	0	0
0.25	0.588939	0.25	0.689764
0.5	1.175323	0.5	1.385451
0.75	1.70181	0.75	2.040525
1	2.241841	1	2.6931
1.25	2.767699	1.25	3.321473
1.5	3.327727	1.5	3.960199
1.75	3.931096	1.75	4.634251
2	4.547974	2	5.318623

Trade and Development: A Modified Model Approach and the Role of the Government

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Abstract

In mid-20th century, the rapid growth of East Asian countries introduced trade into the ongoing discussion surrounding economic development. This paper proposes several modifications to improve models of development by analyzing trade data. The proposed framework is then used to compare the development of sub-Saharan African countries to that of Asian and Latin American countries, testing the effects of several factors on their development. The major finding of this paper is a causal relationship between government size and economic development, which differs based on the economy's "sustained comparative advantage."

1. Introduction

With the independence of former colonies, 20th century economists were tasked with the agenda of developing previously colonized nations. Influenced by the Keynesian theory prevailing at the time, various economists suggested comprehensive economic models that generalized the process of development, emphasizing government intervention and capital accumulation (Rostow 1959, Rosenstein-Rodan 1943). However, government inefficiencies highlighted by stagflation in the 1970s, the Latin American debt crisis, and the failure of planned economies in the 1980s shifted the discussion away from the role of the government and towards laissez-faire economics (Lin 2011). Meanwhile, the success of East Asian economies and their import-substitution and export-oriented development strategies in the 1960s introduced trade into the ongoing debate.

The relationship between trade and economic development remains unclear for several reasons. First, while classical Ricardian theory postulates trade as fundamentally beneficial by the laws of comparative advantage, there is a clear difference between "growth" and "development." While growth refers to the positive progression of an economy, usually measured in terms of Real Gross Domestic Product (rGDP henceforth), this paper defines development as the earlier period of growth when structural changes occur to an underdeveloped economy that ultimately allows it to achieve sustainable growth (Rostow 1959). That is, as the developing economy experiments with various industries, they come to an eventual

understanding of their relatively static endowments[1] and settle on a non-static yet consistent long-term comparative advantage. However, there is still debate on whether or not trade is beneficial during this period of development. Proponents claim that trade improves resource allocation, thus encouraging productivity growth and allowing domestic firms to achieve economies of scale. On the other hand, pessimists argue that allocation based on static comparative advantage prevents industrialization and instead transfers income to their developed partners (Kavoussi 1985).

Regardless of the effects of trade, observing trade data provides valuable insight into the dynamic structure of developing economies. By reversing the logic of comparative advantage, many have theorized that trade data could explain changes not only in economic factors but also in non-economic factors that have indirect effects on the economies' comparative advantage (Balassa 1965). Another model known as the "Wild-Geese Flying Pattern" of Development proposed a homogeneous trajectory of economic development which can be gauged by trade data (Akamatsu 1962). Notably, both models reflect the faulty nature of the commonly used metric for analyzing development: per capita rGDP. While the metric does reflect an aspect of development—increases in living standards—it is biased and may easily misrepresent the level of development as defined earlier.

The objective of this paper is twofold. First, this paper assesses and modifies existing models of economic development to produce an index that measures the level of development using trade data. Second, panel data regression and instrumental variable (IV) regression analyses are conducted using the index to study whether a causal relationship exists between the size of the government and the proposed index. The paper is organized as follows. Section 2 presents an extensive literature review on the topics of development, trade, and the government, and Section 3 proposes modifications to existing models. Finally, Section 4 presents the findings of the described empirical research.

2. Literature Review

2.1. Models of Development

With the rising agenda of industrializing previously colonized nations, various models of development arose in the mid-20th century. Many attempted to explain the process of development as a linear progression through discrete stages. Sir Arthur Lewis, describing the two stages of development—agricultural and industrial—emphasized the importance of government-sponsored redistribution of labor from the former to the latter (Lewis 1954). Walt Rostow explicitly set discrete stages in his Linear Stages of Development Model, claiming that early economies go through five stages of development in an orderly fashion: 1) traditional society, 2) preconditions for take-off, 3) take-off, 4) drive to maturity, and 5) age of high mass consumption (Rostow 1959). Although there are subtle differences, all these models emphasize the shift in focus from agriculture to capital with an emphasis on the role of the government.

One notable model is Akamatsu's "Wild-Geese Flying Pattern" of Development. In his model, Akamatsu claims that industry-specific trade behavior changes over the course of development; therefore, by tracking trade patterns, one

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[1] The static endowments refer to a set of both economic and noneconomic factors that play into the composition of an economy, such as cultural norms or traditions.

could theoretically estimate the stage of development an economy is situated in. The model assumes an import-production-export sequence, reflecting the import-substitution and export-orientation strategies employed by East Asian countries. In this model, Stage 1 is defined by the introduction of consumption industrial goods from developed countries, which is made possible by the revenue from export of raw materials. Stage 2 is marked by the start of domestic production of the previously imported industrial goods. By then, the nation has successfully internalized the factors of production required to produce these goods. At the same time, production of such goods reduces demand for their imports, which is replaced by imports of capital goods. In Stage 3, surplus produce of industrial goods is exported, and the production of capital goods begins (Akamatsu 1962).
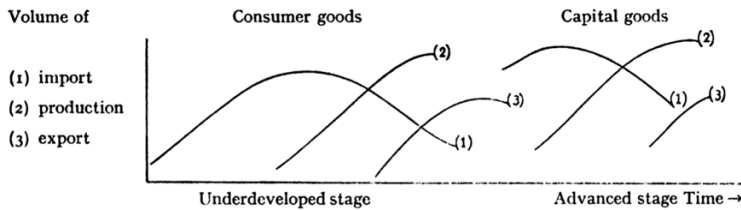
Figure 1. *Akamatsu's "Wild-Geese Flying" Pattern of Development (1962)*

A brief assessment of Akamatsu's model using contemporary data of eleven countries that developed in recent decades, particularly in the 1980s and 1990s, demonstrates the points under which these models were heavily criticized. The proposed method of discretely dividing stages based on the single identifiable point of transition—peaks of relative trade volume (exports/imports divided by rGDP)—has been used. Four indices were calculated in this manner: years between 1) maximum relative exports and maximum relative imports in consumption goods, 2) maximum relative exports and maximum relative imports of capital goods, 3) maximum relative imports of capital goods and maximum relative exports of consumption goods, and 4) maximum relative exports of capital goods and maximum relative imports of consumption goods. From the substantial frequency of negative values in Table 1, as well as the lack of any identifiable pattern in the indices, the need for a more consistent index becomes more pronounced.

Table 1. *Assessment of Akamatsu's Model in Developed Countries (1989-2019)*

Countries	Index 1	Index 2	Index 3	Index 4
Brazil	-9	4	-3	-8
China	13	0	0	13
India	5	5	-5	5
Indonesia	-10	2	0	-8
Hong Kong	-18	6	21	9
Malaysia	-9	2	-4	-11
Mexico	2	2	-2	2
Thailand	-6	2	-3	-7
Turkey	8	22	-22	8
Singapore	-3	0	-4	-7
South Korea	-24	3	19	-2

These models of development were heavily criticized for many reasons. Firstly, the ambiguous descriptions of what defined each stage and lack of substantiating attriubtes to each stage made these models difficult to apply. This was even expressed by Rostow himself, who acknowledged that the transitions between stages cannot be easily defined or even identified (Bauer and Wilson 1962, Rostow 1959). In addition to the seemingly arbitrary definitions of intermediate stages, the problem of generalizing based on only few cases of development did not go unnoticed (Cairncross 1961). Others expressed concerns over identifying discrete stages; as contemporary analysts put it, levels of development should be expressed as a "continuum . . . not a dichotomy of two economic development levels" (Lin 2011). While criticism was most pronounced for Rostow's model, the same arguments could be applied to the other two models as well, for Lewis's Dual Sector Model does not provide clear indication of a transition between stages and implies a Eurocentric perspective, not to mention the great ambiguities of transitions in Akamatsu's Model.

2.2. Trade-Based Indices

In tandem to Akamatsu's work, various economists have attempted to use trade data as a proxy for other variables, with the most significant among the variables being comparative advantage. While the classical Ricardian and Heckscher-Ohlin models are based on static comparative advantage, various economists have pointed out the importance of identifying a dynamic comparative advantage (Rostow 1959, Redding 1999). The first to have proposed the idea of using trade data to determine dynamic comparative advantage was H.H. Liesner, who, drawing from Ricardian theory, claimed that a country would specialize on commodities in which it experiences a comparative advantage (Liesner 1958). Later, Balassa coined the term "revealed comparative advantage (RCA)" for this concept, referring to the way by which trade data can reveal the instantaneous comparative advantage of an economy (Balassa 1965).[2] In essence, the index shows the significance of a country's exports to imports, as well as the relative growth it has experienced over two time periods.

$$\frac{1}{2}\left[\frac{x_{ij}^l}{m_{ij}^l} + \frac{x_{ij}^l}{m_{ij}^l} \cdot \frac{x_{ij}^l}{m_{ij}^l} \div \frac{x_{ij}^o}{m_{ij}^o}\right]$$

The advantage of using the RCA was simple; it accounted for comparative advantage that reflects not only relative costs but "differences in non-price factors" as well (Balassa 1965). If valid, such indices had the capacity to transcend the sole analysis of factor endowments or factor prices, as it would have been able to account for cultural, societal, and other noneconomic determinants of specialization. In turn, one would have been able to significantly improve the accuracy of comparative advantage estimations as well as the effectiveness of foreign trade policies (Vollrath 1991). Since then, many have produced variants of the model (Hillman 1980, Bowen 1983, Yeats 1985, Marchese and De Simone 1989). Nevertheless, the substantial incoherence in past measurements of various RCA indices signaled a warning against using such indices (Ballance et al. 1987).

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[2] In the equation below, (x) = exports, (m) = imports, (i) = country, (j) = commodity, and (l) and (o) represent different time periods.

To apply this model in understanding or ranking growth, there needed to be an objective system that determines the sophistication of each commodity of a nation's comparative advantage. The leading work in the field is the "sophistication" trade measure, in which the income of the exporting nation is used to determine the level of sophistication of a commodity (Lall et al. 2006). In turn, this index makes it possible to describe an economy's level of structural sophistication and to track growth using the structure of their exports. However, the exclusive focus of these models on exports makes it difficult to apply these models to development economics because they exclude import volume trends, a crucial component in development based on import substitution. While analyzing exports may suffice to explain structural differences in developed economies, the full picture of structural changes in developing economies cannot be captured without observing imports. Thus, the risks associated with assessing development using growth theories and models must also be noted.

2.3. Role of the Government

Until neoclassical economic theory in the 1970s, the prevailing growth and development theories strongly emphasized the role of the government. Lewis's Dual Sector Model required the government-sponsored reallocation of labor (Lewis 1954), and government assistance played a crucial role in Rosenstein-Rodan's Big Push Theory (Rosenstein-Rodan 1943). Many others held similar views, largely due to the then-prevailing influence of Keynesian economics. Such a large economic role of the government was justified under two arguments: 1) governments provide infrastructure that facilitates development, and 2) governments offset the effects of market failures and lead investments crucial to development (Krueger 1990). Thus, the prevailing view was that to foster investment crucial to industrialization, government intervention was necessary, as the laissez-faire economic system did not function in the context of developing economies.

However, various economic events starting from the 1970s challenged the ability of governments to correct market failures, adding nuance to our understanding of the government's role. With the stagflation of the 1970s, the downfall of planned socialist economies in the 1980s, and the Latin American debt crisis, the idea of "government failures" came under the spotlight (Lin 2011). These examples changed the way governments were perceived. They were no longer seen as selfless, benevolent, and costless organizations. Governments were subject to lobbying and political pressures which created massive inefficiencies by protecting and thereby encouraging infeasible industries (Krueger and Tuncer 1982). Moreover, under the realization that administrative and organizational resources are scarce, some started speculating that government activity may induce rent-seeking behavior (Krueger 1990). Indeed, the government remained a vital component of development as, compared to the private sector, they had a comparative advantage in initiating large-scale activities. However, such series of events made the government-centric approach now obsolete, paving the way for the neoclassical, laissez-faire system of development.

3. Theoretical Framework

While the models introduced above contain great potential in theory, the feasibility of directly applying these models to development economics is low because of two critical assumptions: the assumption of comparison and the assumption of

homogeneous trajectory of development. Firstly, various trade-based indices such as the RCA attempt to account for structural changes by comparing the exports of a country to other nations or global exports. A flaw in this logic is that these assume that developing and developed economies behave in the same manner in the global market. The truth is quite the opposite. Developing economies are "price-takers" in the global market; they possess extremely small market shares due to the lack of infrastructure and subsequent lack of capability to realize economies of scale. Moreover, structural changes would be less induced by exogenous variables than by endogenous variables throughout the period of development. As a result, producing such indices based on exogenous variables heightens the possibility of misrepresenting structural changes in an economy. Therefore, to accurately demonstrate the shifting patterns of an economy, trade data must be placed relative to domestic growth (rGDP) and relative to each other (exports/imports).

Second, various models above assume a homogeneous trajectory of development, as seen in the models themselves as well as the application of the sophistication measure of exports. Indeed, the foundation of this paper rests on the certain homogeneity of the development process. For instance, it is reasoned that an economy can only begin exporting capital goods after possessing the capacity to produce consumption goods, as capital goods require significantly more infrastructure and capital per worker. But the period of development does have an end, and it only refers to the period during which an economy settles on a structure that allows sustained growth. The industry preferred by the settled structure, then, does not necessarily have to be the capital industry, but can be the consumption goods industry as well, exemplified by the heavy focus on consumption goods in certain developed OECD countries such as France and Switzerland. Models based on this assumption ignore the significance of non-economic factors as well. As a result, one must be cautious in assuming that capital production is the ultimate stage of development.

To address these two points, the models above can be assimilated into a comprehensive framework for understanding economic development. First, by analyzing trade behavior relative to domestic rGDP as in Akamatsu's model that considers both exports and imports, the first problem is addressed. The second can be addressed by producing variants of Akamatsu's model based on the concept of "sustained comparative advantage." This concept describes that all economies display a certain preference for an industry based on certain permanent factors, economic and noneconomic. That is, when economies complete their process of development and reach sustained growth, their trade behaviors would reflect the specific preference for an industry that stays fairly constant and "sustained" over time.

In Figures 2 and 3, this tendency is represented by the differences in the end behavior of trade curves in the consumption and capital industries of each economy. The model simplifies end behaviors into two types: divergence, representing a comparative advantage, and convergence, representing a comparative disadvantage. This tendency is further illustrated by the tradeoff between these two behaviors. It must be noted, however, that this does not imply static comparative advantage. Instead, this assumption claims that while a diverging economy may continue its diverging pattern, it cannot easily shift into a sustained converging pattern; by doing so, it exhibits a sustained comparative advantage, one that will allow sustained growth in its post-development period through greater specialization, economies of scale, and increasing productivity.

Another important component in this model is the bump-shaped behavior in trade curves in which a nation experiences a comparative disadvantage,

represented by Points D and B in Figures 2 and 3, respectively. In general, this behavior reflects industry-correcting behaviors among developing economies. Based on the assumption that all economies attempt to stimulate both capital and consumption-goods industries, when an economy attempts to promote an industry in which it does not have a sustained comparative advantage, the eventual decline in government subsidies and economic profit pool or the realization of structural disadvantages of the nation would cause a number of producers to exit from the domestic market. After this happens, the level of exports to imports would fall to a sustainable level.
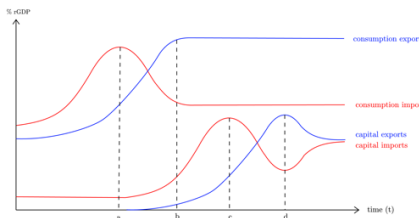
Figure 2. *Development in a Consumption-Based Economy*
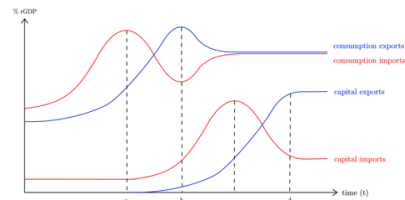
Figure 3. *Development in a Capital-Based Economy*

To analyze all four curves simultaneously, an index can be derived by taking the differences in net relative exports (DNRE). By subtracting the net relative exports (net exports divided by rGDP) of the consumption goods from that of the capital goods industry, the resulting value demonstrates the significance of the capital industry in comparison to the consumption industry. Positive values indicate greater significance in the capital industry and negative values indicate greater significance in the consumption-goods industry.

$$DNRE = \frac{(exports_{ca} - imports_{ca}) - (exports_{ca} - imports_{ca})}{rGDP}$$

The benefit of this index is further demonstrated in its graphs derived from the previous variants. As shown in Figures 4 and 5, there are two distinguishable points that indicate transition between the stages Akamatsu suggested: points C and D. On the graph above, these indicate the year of maximum relative capital imports and the year of maximum relative capital exports, respectively. By analyzing changes in the DNRE index over only this identifiable period, it is possible to avoid making the assumption of homogeneous trajectories of development, as increases in the DNRE index over this period would indicate increases in the level of development rather than an increased preference for the capital industry. Additionally, assuming that the period of development has ended, the end behavior serves as indicators of the economy's sustained comparative advantage, with negative values denoting preference for the consumption-goods industry and positive values signifying that for the capital industry.
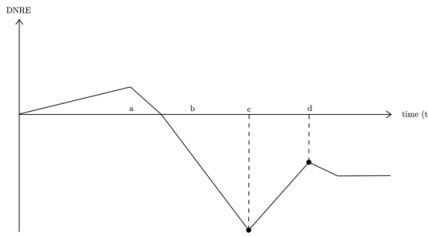
Figure 4. *DNRE Curve in a Consumption-Based Economy*
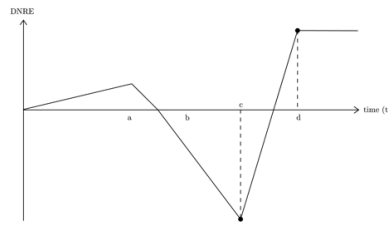
Figure 5. *DNRE Curve in a Capital-Based Economy*

The validity of this index is supported by the strong positive correlation between per capita rGDP and DNRE for the 11 developed economies throughout the period 1989-2019 as shown in Figure 6. Also, a consistent, relatively unbiased trend can be observed across most of the 11 countries, demonstrated in Figure 9. Among these countries, many display clear transition points (Points C and D), as well as a steady increase until they reach sustained comparative advantage. The different patterns of end behavior elucidate the validity of both variations of the model, as economies specializing in capital production (Hong Kong, South Korea) show different end behaviors than economies specializing in consumption goods production (Mexico, Brazil, Türkiye).
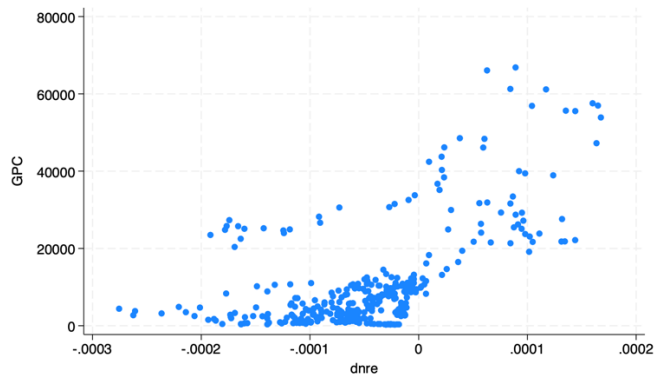
Figure 5. *DNRE v. GDP per capita in developed economies (1989-2019)*

For the modified model to be put into use, several critical assumptions, in addition to the idea of sustained comparative advantage and industry correcting behavior, must be justified. First, the model assumes that regardless of an economy's endowments, it follows the pattern of producing consumption goods and then capital goods (followed by exports in relative industries). The greater capital accumulation needed to stimulate the production of capital goods (than that of consumption goods) explains for the sequence of development. However, a key factor is that the economy, either through government support or foreign investors, attempts to grow its capital industry. Although this is a bold assumption, there are past examples that support this claim; for instance, Brazil and Mexico, despite

sharing an end behavior inclined towards consumption goods, have shown substantial periods of growth in the capital industry in their DNRE graphs. Second, it is assumed that tastes and global demand are relatively consistent over time, and that tariff rates are equal across commodities; only by doing so can the trade data properly reflect the changing structures and endowments of a nation instead of tracking trade openness. Consequently, it is assumed that increasing exports indicate growth in that particular industry.

4. Empirical Analysis

4.1. Data and Methodology

The produced index is now used to test the effects of commonly referenced factors of development. The percentage of government spending to rGDP was used to represent the size of government, and changes in foreign direct investment (FDI) was used to represent the influence of foreign investors. Lastly, the percentage of secondary school enrollment was used to represent human capital. A dummy variable EB (end behavior) was created to represent the differences in endowments and to produce interaction terms, where EB = 0 represented a consumption good-intensive economy (DNRE2019 < 0), and EB = 1 represented a capital good-intensive economy (DNRE2019 > 0). Lastly, a fixed effects regression analysis was chosen, as it is inappropriate to use the index to compare the levels of development across countries. By doing so, one would repeat the mistake of assuming structural homogeneity in developed economies.

$$DNRE_{it} = \beta_0 + \beta_1 GOV_{it} + \beta_2 FDI_{it} + \beta_3 HCAP_{it} + \beta_4(GOV_{it} \cdot EB) + \beta_5(FDI_{it} \cdot EB) + \beta_6(HCAP_{it} \cdot EB) + \delta_i + \varepsilon_{it}$$

As for the panel data, the cross-industry trade data was taken from the World Integrated Trade Solution (WITS) database (Bank nd). Data for rGDP, government spending, FDI, and partially human capital was extracted from the World Bank Open Database (Bank 2021). Finally, parts of human capital data were taken from the International Monetary Fund (IMF) Database (Fund 2022). Unfortunately, trade data was limited, only capturing the period 1988-2020 (and was even more limited in certain cases). Certain countries were excluded due to an extreme lack of data. A total of 11 developed countries and 35 sub-Saharan African (SSA henceforth) countries have been selected.[3]

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[3] The 34 SSA countries are Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Comoros, Democratic Republic of the Congo, Republic of the Congo, Cote d'Ivoire, Ethiopia, Gabon, Ghana, Guinea, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Seychelles, South Africa, Sudan, Tanzania, Togo, Uganda, and Zimbabwe. Other SSA countries were not considered due to a lack of data.

Table 2. *Fixed Effects Analysis on DNRE Index*

Variable	Developed Countries	Sub-Saharan Africa
Government Spending	-0.00205***	-0.005116***
	(0.000715)	(0.00150)
FDI	-0.0000916	-0.0009587
	(0.0003629)	(0.0025813)
Human Capital	0.0016125***	0.0019691**
	(0.0001802)	(0.0008407)
Government Spending * EB	0.0087765***	0.0044638**
	(0.0013089)	(0.0022498)
FDI * EB	-0.0039642	0.0009147
	(0.0006952)	(0.0025904)
Human Capital * EB	0.003508***	0.0010236
	(0.0006952)	(0.0009995)
Observations	270	450
Country Fixed Effects	Yes	Yes
Time Fixed Effects	No	No
R^2	0.5508	0.0542
Countries	11	34

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

4.2. Results

The results of the empirical research are summarized in Table 2. Two endogenous variables displayed a statistically significant relationship with the index in both groups: government spending and human capital. An interesting observation can be made regarding government expenditures. The interacting term GOV · EB yielded coefficients of the opposite sign (+) compared to the non-interacting term (-) in both groups, with a p-value less than 0.01. This signifies a significant difference in the relationship between government size and the index across countries with different comparative advantages. In the case of developed countries, the magnitude of the coefficient of GOV · EB was greater than that of GOV, indicating a positive correlation between government spending and capital industry development in countries with strength in their capital industry, while the opposite was observed in countries strong in their consumption industry. A similar trend is observed among SSA countries, albeit to a lesser degree, as the magnitude of the coefficient of GOV is greater than that of GOV · EB. The effects of human capital are more complex to analyze. Among Developed Countries, human capital was positively correlated with DNRE, and among capital-intensive countries, the correlation was even stronger. However, while there was a strong correlation between human capital and DNRE among SSA countries, no statistically significant difference was observed between economies with different sustained comparative advantages.[4]

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[4] This may have been caused by the fact that the end behavior of many of these countries may have been misrepresented, as they could still be in their developing stages and have not yet reached sustainable growth.

4.3. IV Regression

In order to test whether the variable of interest, government expenditures, has a causal impact on the DNRE index, an instrumental variable (IV) regression was conducted. For this regression, military spending has been selected as the IV. To be considered valid, an IV must qualify in two conditions: relevance and exogeneity. The first condition states that the instrumental variable shows a statistically significant relationship with the endogenous variable of interest. The second states that the IV must not be correlated with the error term of the original regression equation. In other words, it states that the IV cannot impact the dependent variable except by affecting the endogenous variable (GOV).

First, we can assume that the condition of exogeneity is met as it can be safely assumed that the size of military spending cannot influence industrialization unless by means of influencing the size of the government. To check for the relevance condition, an Ordinary Least Squares (OLS) Regression has been conducted, regressing government expenditures on military spending. As the p-values of military spending size in both groups are statistically significant, we can verify the validity of using military spending as an instrumental variable.

$$gov_{it} = \alpha_0 + \alpha_1 Military\ Spending_{it} + \alpha_2 FDI_{it} + \alpha_3 hcap_{it} + \varepsilon_{it}$$

$$gov'_{it} = \gamma_0 + \gamma_1 Military\ Spending_{it}$$

$$DNRE_{it} = \beta_0 + \beta_1 gov'_{it} + \varepsilon_{it}$$

Table 3. *Testing the Relevance Condition for IV Regression of Government Expenditures (1988-2020)*

Variable	Developed Countries	Sub-Saharan Africa
Military Spending	0.8795723*	3.454287***
	(0.4579156)	(0.2960558)
%FDI	0.0343124	0.0142671
	(0.0727117)	(0.0184964)
Human Capital	0.1450134***	0.2167104***
	(0.0209792)	(0.0154796)
Constant	10.53251***	7.792861***
	(1.953165)	(1.018386)
Observations	253	519
R^2	0.1660	0.3484

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Subsequently, by predicting values of the size of government using the size of military spending, we can conduct a regression on the DNRE index. As both predictions show statistically significant results, we can conclude that there is a

causal relationship between military spending and level of development based on the DNRE index. Ultimately, with significantly low p-values in our last regression using the predicted values of government size, we can conclude that there is in fact a causal relationship between government size and the level of index for both groups over the period measured.

Table 4. *Second-Stage IV Regression with gov'*

Variable	Developed Countries	Sub-Saharan Africa
GOV'	-0.0158179*** (0.0036761)	-0.0037699*** (0.0010481)
Observations	319	776
R^2	0.0552	0.0164

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

5. Discussion

The main finding from the empirical research is the causal relationship between the size of the government and the DNRE index in both groups. Comparing the coefficient of the interacting and non-interacting terms, the size of the government was found to have different impacts on countries based on their sustained comparative advantage, which supports the findings of past research concerning the endogenous variables' impacts on export upgrades (Zhu and Fu 2013). In countries possessing a comparative advantage in consumption goods, the size of the government seemed to have a negative impact on the DNRE index, while it had a positive impact on the index among those with a comparative advantage in capital goods. But why is this so? While it is possible that certain industries—capital-intense industries—naturally prefer government intervention, this inference assumes that the quality of the government is constant across countries. This cannot be assumed. As Figure 7 below indicates, there is a significant difference in average corruption control in developed countries. However, the differences seem to be minimal in SSA countries, although this may be that these countries haven't yet reached their sustainable comparative advantages.
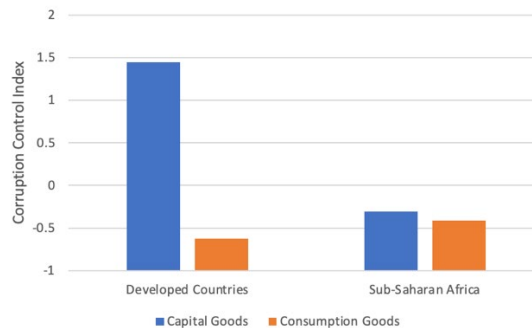
Figure 7. *Comparison of Average Corruption Control Index Scores (1989-2019)*

Nonetheless, there are reasons to believe that differences in sustained comparative advantage (end behavior) were caused by structural differences between the two types of industries and corresponding differences in the role of the government. For instance, developing capital industries necessitates infrastructure, which is largely a public good that only the government would be incentivized to provide for. Similarly, a bigger government size could be correlated with public education quality which can spur development in capital industries (human capital). Also, capital industries have high barriers to entry; as a result, the impact of subsidies may be greater in inciting growth of the capital industry. On the other hand, this may not be the case in consumption-growth based economies. Oftentimes, consumption-good industries face lower barriers to entry, as the amount of capital needed for each worker is smaller; as a result, subsidies would be detrimental as they harm domestic competition. In addition, the focus on manual labor within such industries may affect the impact of the role of the government as a regulating institution. As a result, structural differences and differences in the role of the government in each industry may be the cause of the different impact of government size on industrial development.

However, the limitations of the research should not be ignored. There are various ways in which the assumptions of the model may pose questions about the validity of the research. Possible assumptions that may have affected the validity are the assumption of industrial correction and the assumption of tariff consistency. In addition to these assumptions, it is risky to determine the sustained comparative advantage among SSA countries, as there is the possibility that they have not yet reached sustained growth. This may have affected the validity of the EB dummy variable. Most importantly, however, the results of the empirical research may have been biased due to the small number of observations, countries, and time periods encompassed by the panel data, which was especially the case among SSA countries.

6. Conclusion

This paper proposes a modified model of development that better demonstrates the process of development, which can be more reasonably generalized to other regions as well, based on recent observations among developed countries. Specifically, Akamatsu's "Wild-Geese Flying Pattern" of Development has been modified, largely by creating two variants based on each economy's sustained comparative advantage." To account for changes in all four curves, the DNRE index has been derived, and using the index, regression analyses have been conducted to observe which institutions have had significant impacts on development between different groups. Three institutions were tested (government, foreign investors, domestic labor force) for two groups (Developed Asian/Latin American countries and SSA countries). The most significant result from the analysis is that the relationships between government size and level of development differ across economies with different endowments, or sustained comparative advantages. Results of the IV regression, which utilized percentage of military spending, show that there is a causal relationship between government size and level of development.

The findings of this research contribute to our understanding of economic development, explaining the logic behind revealed comparative advantage and applying it to quantify the changing structures of developing economies. Further research may be conducted on testing the assumptions of the modified model as well as identifying exogenous variables that affect the appropriateness of applying the model. Also, the modified model may be applied to a more comprehensive empirical analysis of endogenous variables and their impacts on industrialization. However,

applications of this index must entail a detailed study of other indicators that ensures that the patterns of change in the index are indeed an indication of development rather than fluctuations over time. Lastly, from policy perspective, our findings suggest that selective expansion of government spending may be advantageous, particularly if its sustained comparative advantage could be reliably measured or predicted. This targeted approach could potentially catalyze and accelerate the pace of economic development.

7. Appendix

Figure 8. *DNRE Curves of 11 Developed Countries (1989-2020)*

The figure above shows the DNRE curves of 11 developed countries from 1989 to 2020. As mentioned, clear transition points exist for many countries including Brazil and Mexico. However, due to the presence of outliers, interpreting these curves to determine the sustained comparative advantage of an economy requires a careful observation of overall trends. Regardless, the graphs also illustrate the lack of data as for certain countries, it is difficult to conclude their sustained comparative advantage.

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✵

Treatment of Microplastic-Related Pollution in Sewage Along the Yangtze River: Waste Water Treatment Plants Versus Constructed Wetlands

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Abstract

As the Yangtze River sees an increase in industrial development and urbanization, microplastics (MPs) in wastewater create increasingly significant environmental hazards. At the same time, an alternative sewage treatment method in the form of constructed wetland is growing rapidly in effectiveness and efficiency. Hoping to determine the relationship between the presence of MPs with other pollutants and the most potent treatment method with minimal negative environmental impact, this paper summarizes previous research and local reports globally. It found that, while heavy metal, PPCPs and antibiotics coexist with MP particles, their presence cannot be causatively linked to general population density in cities; instead, in terms of treatment approaches, the reversed phenomenon can be explained by the difference in applied techniques. This paper also concluded that constructed wetland is an equal or greater treatment method for sewage MP-related pollution treatment when compared to traditional forms. The results from our field research supports the latter assumption, with data showing a higher removal rate of MP and components in terms of shape, sizes and chemical properties that pose smaller hazards to the Yangtze River water quality and aquatic ecosystem.

1. Introduction

1.1. Microplastic

Plastic is one of the most widely used materials in the world, with at least 400 million tons produced per year.[1] However, in recent years, the emergence of microplastics (MPs) in surface water bodies has become increasingly serious. Microplastic is a kind of plastic particle with a diameter of less than 5 mm. Their large surface area and light weight make them the main carrier of multiple water contaminants, allowing them to

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[1] Amaral-Zettler L. A., Zettler E. R., Mincer T. J. Ecology of the plastisphere [J]. *Nature Reviews Microbiology*, 2020, 18(3), 139-151.

carry one or more pollutants that pose a worldwide threat to aquatic ecosystems. [2] MPs can be divided into LDPE (low-density polyethylene), HDPE (high-density polyethylene), PP (polypropylene), PS (polystyrene), PET (thermoplastic polyester), PVC (polyvinyl chloride), CA (cellulose acetate), PA (polyamide) and PES (polyester fiber). According to their shapes, MPs are also categorized into fragments, spheres, fibers, films, foams, and beads. Fibers are the most abundant, while film and foam-shaped MPs bear an average abundance of about 10% or less. [3] Additionally, MPs can be divided by colors, ranging from transparent, white, red, green, black, blue, and orange. Finally, according to their sizes, the most commonly used categories are 25 μm, 100 μm, and 500 μm. In the feed water of sewage treatment plants, approximately 70 percent of MPs exceed 500 μm; more than 90% of MPs in the effluent, on the other hand, are less than 500 μm, while about 60% of MPs in some samples are less than 100 μm. [4]

Understanding the varied nature of MPs is crucial when considering their impact on ecosystems. MPs not only cause physical harm to organisms through ingestion, but also release or adsorb pollutants directly or indirectly toxic to the ecological environment, thereby causing potential harm to the safety of marine, freshwater, soil, and other ecosystems [5] in these aspects: (1) blockage in feeding organs of aquatic animals and consequent physical harm [6]; (2) toxic plasticizers and dyes released upon ingestion [7]; (3) co-existence with organic pollutants, heavy metals, and pathogenic microorganisms that enables their fast absorption in organisms, increasing the bio-concentration of the food chain and thus triggering toxic effects after animal feeding, indirectly affecting marine organisms and human health.

Studies have shown that microplastics are widely found in both marine and freshwater ecosystems, as well as soils and sediments, and even in drinking water, human waste, and polar environments. [8] In 2011, Claessen et al. [9] found that the MPs in the Belgian port reached 68~390 kg, and in 2013, the data collected in the Venetian Lagoon was as high as 672~2 175 kg. The MP content of Khusugul Lake in Mongolia also reached 20,264 kg. [10] In typical treatment facilities, the amount/concentration

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of? MPs in wastewater have been reported to be as high as 15.7 pcs/L and 180 pcs/L.[11] A large number of MPs enter the water body through the effluent of sewage treatment plants, which is considered to be an important source of MPs.[12] In addition, the vast majority of MPs removed by the sewage treatment process are trapped in sludge. With improper disposal of sludge and land use, these MPs end up in the soil. Li[13] and other studies found that in 2015, the number of MP particles entering the soil environment through sludge in China reached trillions of billions. Unfortunately, at the same time, sludge MPs have significantly enhanced adsorption potential for heavy metal pollutants such as Cd.[14]

While the environmental impacts of MPs are concerning, their link to human activities offers potential insights into future reduction of their occurrence in aquatic environments. MP is found to be positively related to the type and intensity of human activities around water bodies. Many studies have shown that the content of MPs in the natural environment correlates with population density, as proved in the central industrious section of the Yangtze River and in the Rhine and River Thames in the UK.[15] At the same time, in the Chicago water system, the concentration of MPs in rivers exceeded that of the ocean, and the effluent from sewage treatment plants was an important source of MPs.[16] Most of the types of MPs in wastewater are related to daily plastic products. For example, PES mostly comes from laundry washing, and the most abundant types of MPs in personal cosmetics and detergents are PE, PP, and PS. According to their sizes, recent studies showed that smaller MPs less than 25 μm in size have significant abundances in wastewater.[17] This result is consistent with Atlantic observations, where MPs below 40 μm accounted for 64% of all detected MP particles, with more than half being less than 20 μm in size.[18] As for shape categories, fiber-shaped MPs are related to the discharge of a large number of chemical fibers in household laundry wastewater. MP films and foams can come mainly from plastic bags and packaging products, while granules come mainly from personal care products. Wastewater MPs may also depend on the land use of the surrounding environments and transportation-related emissions, such as MPs released by tire and brake wear and residents' preference for wearing synthetic clothes or using plastic

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products.[19].

1.2. Constructed Wetlands

Alternatively to widely used sewage filtration and sedimentation facilities, MP pollution in sewages can also be treated with constructed wetlands (CWs) before entering surface water ecosystems. CWs are artificial systems designed to simulate the functions of natural wetlands in water quality improvement. They primarily consist of sand, gravel, microorganisms, and selected pollution-resistant plants. A variety of sewage (domestic sewage, agricultural wastewater, refinery wastewater, landfill leachate, and factory wastewater) [20] is purified by the physical, chemical, and biological synergy of the natural ecosystem. After the Reform and Opening- up, the southern part of China, which is supported by the Yangtze River water system, went through exponential economic growth and rapid urbanization, accompanied by wastewater's increasing in quantity and expanding in distribution. [21] While the conventional WWTPs (wastewater treatment plants) are limited in the capacity and diversity of sewage treatment, CW technology effectively deals with this shortage. It has thus been widely adapted along the Yangtze River with the advantages of low costs, high efficiency, and better ecological services.[22]

Having understood the importance of CWs, it is pertinent to delve deeper into how they are applied in wastewater treatment. Although usually combined with other treatments, CWs are playing an increasingly important role in China's sewage water purification with their diverse application scenarios. A survey[23] showed that, in more than 13 provincial-level administrative regions across China, CW systems have covered more than 30% of the surface water systems with treatment scales ranging from 1000 m^3/d to 20,000 m^3/d. Many examples of secondary or tertiary treatment facilities combining different types of CW units in one overall system can be found in the Yangtze River. However, while CW systems are widely applied in small-scale or final-stage water pollution control, WWTP is still the most common way to treat wastewater in the Yangtze. By 2010, the gross of wastewater treatment by CWs only accounted for 0.82% of the total value of the two processes.[24] Nevertheless, due to CWs' combined financial and ecological potential, the difference between usage rates of CWs versus WWTPs is decreasing drastically. Since 2003, the growth rate of CW capacity has stayed significantly and continually higher than that of WWTPs, as centralized national policy and increasing technical feasibility in local situations have both been enhancing the construction of industrialized CWs in China. For instance, during the "Eleventh Five-Year Plan" period (2006–2010), CW sewage went from 53.68 billion tons in 2006 to 61.73 billion tons in 2010. A series of policies greatly

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supported the construction of the CWs by offering vacancies for industrious developments and competitions. CWs also offer a special and localized advantage over conventional WWTPs in terms of environmental protection through the reuse of effluent. In 2010, the number of CWs providing effluent for agricultural irrigation increased by 12.5% from that in 2009.[25] As many mid-to-small towns along the Yangtze River rely on agriculture as the local pillar industry, environmental and financial potentials of CW effluent reuse are limitless.

Although previous research has made remarkable progress, a large academic vacuum still exists regarding the occurrence of MP particles in wetlands, preventing further application of the technology in treating the rising amount of urban sewage polluted with increasingly complicated contaminations. Factors influencing the vertical migration of MPs in wetland systems are extraordinarily complicated. They include CWs' physicochemical properties, accelerated deposition of material combinations (mineral adsorption and bio-flocculation), and resuspension. Minerals such as heavy metals tend to be adsorbed on the surface of negatively charged MPs, while algae aggregation tends to be adsorbed on positively charged MPs[26]. MPs are also taken up by organisms and integrated into sediments, making them seemingly undetectable in wetland systems. Another study showed that the influent concentration of horizontal undercurrent CWs in water purification systems was as high as 6.45 capsules per liter, and the effluent concentration was 0.77 capsules per liter, resulting in a retention rate of 88%[27]. Photo-degradation and micro-biodegradation can further reduce the volume of MPs, even to nanoparticle sizes. Coupled with the exogenous influx, wetland systems are also the main gathering place for nano-plastics. Despite their apparent protection of surface water environments as tertiary treatment, little is known about CWs accommodating and accelerating MP/NP accumulation, which harms ecological stability.

While multiple studies have disagreed upon the removal rate or mechanisms of MPs in CWs[28], similar research on the Yangtze River watershed, due to its intertwined climatic, geological, and ecological conditions, only generates? more complexity. It is also unclear whether MP accumulation in this watershed adversely affects CWs. According to previous studies, MPs can change the nitrification and denitrification functions of microbial communities in sediments, while also affecting plant growth and producing oxidative stress[29], which are both harmful to the aquatic ecosystem. Therefore, as a wastewater treatment system composed of microorganisms, substrates, and plants, the adverse effects of MPs need to be further clarified.

Thus, it is important to strengthen the research on the effects of MP removal mechanisms in both conventional WWTPs and CWs, and to study the factors that contribute to these differences, including the co-existence of MP and other pollutants, treatment mechanisms, and removal efficiency in CWs

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2. Methodology

2.1. Sources of Data

The paper's primary scope of analysis is the Yangtze River. The Yangtze River originates from the Qinghai-Tibet Plateau and flows east into the East China Sea, with a total length of 6300 km. Yichang and Hukou divide the river into upper, middle, and lower sections, with lengths of 4504 km, 955 km, and 938 km, respectively. The Yangtze River basin refers to the catchment area of the main tributaries of the Yangtze River, spanning across three geological stairs in China. With an area of about 1.8×10^6 km², the basin accounts for 18.8% of the total land area of China. The main water systems in the basin are the Yalong River, Min River, Jialing River, Wu River, Dongting Lake, Han River, and Poyang Lake. At the same time, the Yangtze River Basin is also known as China's "golden belt, " gathering more than 40% of the country's total population and economic output, with an average population density of more than 220 people/km² and showing a gradual increase from west to east. At the easternmost end, near the estuary, the Yangtze River Delta is the most densely populated area in the Yangtze River Basin and even the whole country.

We accessed the secondary data of MP and other pollutant concentrations and removal rates from a total of 22 WWTPs and CWs along the Yangtze River through official records and documents (including the two sites collected by this research). They are categorized in terms of location along the river: upstream section (upstream to Yichang city), middle stream section (Yichang city to Hukou city), and downstream section (downstream from Hukou city). Divided into sewage treatment methods, the facilities either use traditional MP filtration through 0.1 mm-diameter filters, through 0.5 mm-filtration, or combine wetlands with filtration. To fully show the facilities' removal efficiency, the data of pollutant concentration selected for co-existence analysis were collected at or near the end of the final treatment processes, where co-existence was most ideally expressed in solution and sediment samples.

Secondary data came from institutes where the quality and reliability of the data were insured by the local governments and/or international academic reputations. The institutes or organizations that offered data on the Yangtze River included: Nanjing University, Wuhan University of Science and Technology, Changsha University, the Environmental Statistics Bureau of Jiangsu Province, Hehai University, Yichang City Government, and Surface Water Research Institute of Jiangsu Province. Other sources of data or methods worldwide can be found in the acknowledgments section.

As for laboratory analysis, samples are collected in a WWTP and a CW in the suburban Nanjing city where treated water directly enters the river. Nanjing is a city along the middle-downstream Yangtze River. It is a proper site to direct the research for its typical medium-level industrious and domestic water use and advanced water treatment systems, which were built in the 1960s to treat the chemical industrious water pollution and kept being optimized up to the present.

2.2. Data Analysis Methods

Previous research found that many major Yangtze River water pollutants (heavy metals, PPCPs, and antibiotics) are attached to various forms of MP clusters in the water. To describe their co-existence, we adopted SPSS 20.0 Software to perform One-way ANOVA, and used Pearson's test for correlation analysis. We also used CANOCO 5. 0 Redundancy Analysis to deal with the connection of MPs and physicochemical

factors on other pollutants.

2.2.1. Pearson Correlation Coefficient

The Pearson Correlation Coefficient is the analysis of the linear correlation between two different variables. Although this formula is suitable for calculating the connection between the vast majority of two variables, there are certain requirements. The gap between the experimental data cannot be too large, and it must be assumed to be from the normally distributed population, otherwise the calculation results will be greatly disturbed. In our research, all requirements are met.

2.2.2. One-way ANOVA and Tukey Post-hoc Test

One-way ANOVAs compare the means of three or more independent groups to determine if there is a statistically significant difference between the corresponding population means. We used it to determine if the dependent variable, the removal rate of MP-related pollution, changes according to the level of the independent variable, the three treatment approaches as defined earlier. To find how the treatment levels differed from one another, we performed a Tukey HSD (Tukey's Honestly-Significant Difference) Post-hoc Test.

2.2.3. Redundancy Analysis

Redundancy Analysis allows for studying the relationship between two tables of variables. It shows how much of the variation in one set of variables can be explained by the variation in another. In this case, we incorporated the MP-antibiotic co-occurrence concentration with multiple water quality parameters, MP characteristics, and treatment methods. We demonstrated and compared the impact of differences in these parameters on the co-occurrence of MPs and antibiotics in sewage treatment scenarios.

2.3. Sample Analysis

In response to concerns that the precise difference in treatment efficiency of MP-related pollutants was not highlighted in the secondary data collection part, in primary data collection, we conducted the primary data analysis in two typical sites along the Nanjing section of the Yangtze River.

The first sampling date of this study was July 20th, 2023, and sludge samples in WWTP1 were collected from three main places: the fine grid, grit tank, and dry sludge in the sludge dewatering room. Three random points were chosen for sampling at each site. The 2-kg sludge sample was put into an aluminum foil sealing bag with a stainless-steel shovel, mixed up, and transferred to the laboratory for preservation. At the same time, large plastic fragments present at the grid point were collected together to provide a reference for subsequent analysis of the source properties of MPs. The collected sludge and screen slag samples were dried in a 45°C electric blower drying oven for 4 h, passed through a 5 mm-diameter stainless steel sieve, and then set aside.

The second sampling date of the study was July 31st, 2023. We chose CW1 in Nanjing city's easternmost suburban area along the Yangtze River as an experimental final-stage treatment wetland. Similar to the procedures from the first sampling site, three random points were selected at the inlet where influent water flows in the undercurrent section, the interval between the two sections, and the outlet where effluent flows out. For safety issues, the points were located near or directly under the bridges where the stream through the wetland was relatively narrower than average.

A 5L stainless steel water sample collector was used for water sample collection. We passed the collected water samples through stacked 5000 μm, 500 μm, 100 μm, and 30.8 μm pore size stainless steel screens under gravity. After sifting, we rinsed the residue on each screen into 250 ml glass reagent bottles using ultrapure water, and the bottle mouth was sealed with aluminum foil. Each sample was processed 3 times according to the above steps. As for the sediments, we collected same number of samples with stainless steel shovels near the plant root system (10 ~ 20 cm below the surface of the wetland), taking 5 kg of left and right filler, which was sealed and stored in an aluminum foil bag at 4°C. All water and sediment samples were brought back to the laboratory and stored in a 4°C freezer for further processing and analysis.

For the facility samples, we first shook the water sample taken in the field to prevent agglomeration or adhesion of MPs. There were a large number of natural organic impurities in the water sample, so the sample first needed to be digested with 30% hydrogen peroxide for 24 hours, and then washed with ultrapure water three times. Finally, according to the turbidity of the water body, an appropriate volume of water was selected for filtration, and a 0.45 mm glass fiber filter was selected for the filter membrane. After filtration, the filter membrane was glued to the glass dish, and the lid was placed in a dry place to dry.

For the wetland water samples, due to the overall low concentration of suspended solids in effluent samples passing through wetlands, the filtered samples were directly digested by H_2O_2 without density separation. We used 30% H_2O_2 to transfer all the residue on the membrane and inner wall of the filter to the beaker. It was digested at room temperature for three days. We used a 0.45 μm mesh membrane true air extraction (negative pressure of over filtration does not exceed 4 0 kPa) after digestion and transferred the membrane to a glass Petri dish (75 mm) washed with ultrapure water. We stored the membrane at 4 °C for further analysis.

For mud samples collected at the facility, we designed our process based on the fact that considerable numbers of natural organic impurities and other impurities occur in the sediment. First, the larger stones and shellfish in the sediment were picked out, and then a certain quantity of wet sediment was weighed in the triangular Erlenmeyer flask. Then the saturated sodium chloride solution, prepared in advance (1.12g/mL), was added to the bottle. While stirring with a glass rod, the saturated sodium chloride solution was continuously added and, after standing until the sediment was stable, the saturated sodium chloride solution was slowly added to the bottle to the liquid level, and the supernatant after flotation was taken. The above operation was repeated 2-3 times. The hydrogen peroxide was digested and filtered using a 0.45um glass fiber membrane, and the subsequent operation was consistent with the treatment method of MPs in the water sample.

For CW sediment samples, we used ultrapure water after filtration with a 0.45 μm filter membrane to rinse the collected sediment sample. The product was placed in a glass beaker afterward, and the cup opening was covered with aluminum foil and placed in the blast to be dried completely in the blast drying box at 60 °C. We stirred the samples evenly when they were completely dry and used a 5-mm stainless steel sieve for the initial sieve procedure. The sample was then added to the saturated NaCl solution and stirred well for two minutes. After covering the cup mouth with aluminum foil for another 24 hours, we filtered the supernatant with a 10 μm nylon filter membrane. We added the remaining sediment to the saturated NaCl solution to repeat the density separation and membrane filtration process three times, to maximize the extraction of MPs. Finally, all the substances on the filter membrane after flotation filtration were transferred to a beaker. 30% H_2O_2 solution was added, and the digestion was attired by oscillation in a shaker at 6 5 °C, 8 0 r/m for 24 h.

After digestion, the obtained solution was filtered again with a 0.45 μm nylon membrane, and the filtered filter membrane was placed in a clean and dry Petri dish to dry at room temperature, and the MP particles on the filter membrane were observed and treated after drying.

Filter paper containing MPs was examined with a stereomicroscope (SZ61, Olympus, Japan). After visual identification of suspected plastic particles, we transferred the particles from the filter to a clean and smooth cardboard piece, with biological dissection forceps. All particles transferred to the cardboard were counted, color-identified, and sized using a digital camera (DigiRetina 16, Olympus, Japan). Suspected MPs were selected from all samples and detected with Raman microscopy (India, Renishaw, UK).

2.4. Quality Assurance Methods

The collection process was conducted in a closed environment, and we wore cotton lab coats to avoid the air and MPs on the clothes falling into the filter membrane. All observation processes were carried out carefully in fully closed laboratory environments to avoid MP pollution from the air.

To avoid cross-contamination, we carefully washed the extraction equipment with ultrapure water after each sample pretreatment. Ultrapure water samples were tested and analyzed by blank method to avoid potential contamination of distilled water and air in the laboratory.

We applied field blanks and duplicates to ensure that the treatment processes were free of additional MP concentration or any form of disruption to the original existence in the collected samples resulting from the collecting, transporting, or storage processes. We took one additional container to each location and filled them with previously prepared laboratory ultrapure water detected with zero MP per liter. We treated these blank samples with the same procedures during their collection and transportation to the laboratory. If the final testing result of the blank sample was still unchanged at zero per liter, then we assumed that our field sampling process was properly contamination-free. In addition, to improve the reliability of the sampling process, we added one additional duplicate sample in every three locations and compared the two sets of results of the MP detection of the identical samples. If they corresponded within a tolerable difference of 0.005 grams per liter, the reliability of the locating and collecting procedures was proved to be acceptable.

To clarify the error of the wet hydrogen peroxide oxidation method and sodium chloride flotation method on the identification of MPs, a blank control group and a control group with a known number of plastic samples of different particle sizes were added in the experiment to calculate the recovery rate of MPs of each particle size. To avoid the contamination of samples by the environment during sampling and experiments, cotton lab coats and rubber gloves were worn throughout the experiment, and open containers were covered with tin foil after each opening.

To make sure that the MP detection process does not contaminate the samples, for each sample, we collected from the field, we repeated the blank extraction and duplicate methods with identical procedures and materials, using the laboratory's MP-free sample water. In addition, we also included the standard material addition to test the reliability of our experiment. We put 5 g MP-filtered particles, produced by Surface Water Research Institute of Jiangsu Province on the 10th of June, 2023, from MPs collected in the Yangtze River, into 10 l of the MP-free ultrapure water and treated it with the same procedures as other lab samples.

3. Secondary Data Analysis

3.1. Total Organic Carbon

Table 1. *The co-existence of MP particles with other pollutants in treatment sites.*

Facility location	Upstream Section (Tibet to Yichang)	Middle Section (Yizhang to Hukou)	Downstream Section (Hukou to estuary)
TOC	0.38	0.57	0.64
Heavy Metal (in average)	0.25	0.46	0.56
E. coli	0.45	0.12	-0.34
PPCP	0.54	0.47	0.07
Antibiotics	0.66	0.35	0.14
Techniques	Filtration through 0.5mm diameter filters	Filtration through 0.1mm diameter filters	WWTP-CW combined treatment
TOC	0.34	0.67	0.79
Heavy Metal (in average)	0.30	0.24	0.36
E. coli	0.23	-0.10	-0.04
PPCP	0.56	0.49	0.66
Antibiotics	0.70	0.37	0.27

The connection between MPs and water quality in general is between medium to strong (according to official Pearson standards), as can be concluded through the correlation with Total Organic Carbon (TOC). According to *Table 1*, the coefficient gradually increases as the water flows downstream. One of the major reasons for this is urbanization, though occurrence mechanisms and treatment methods also play an important part in determining the co-existence level. In addition, a valuable boost of CW in removing MPs is presented. The correlation coefficient in this case, the p-value, also stands for the level of equity in treating different pollutants. This is because they show similar concentrations in the sludge waste, increasing dramatically from the most traditional to the most innovative among the three treatment approaches.

3.2. Heavy Metals

MPs can accumulate diverse heavy metals, most typically lead (Pb), cadmium (Cd), copper (Cu), chromium (Cr), nickel (Ni), zinc (Zn), etc. Adsorbed/additive heavy metals can also be released from the surface or inside of MPs. Thus, we focused our correlation analysis on these metals specifically. According to *Table 1*, we have seen an average correlation coefficient of 0.45 in all heavy metals and MPs in all sections of the Yangtze River treatment facilities. The most related metals with MP were Pb and Cu, with coefficients as high as 0.56 and 0.58, respectively; while the correlation between MP and Ni was the lowest among the six heavy metals calculated. As the up and middle stream sections have historically applied to industrious construction, the density and efficiency of production in steel factories, chemical factories, and various traditional water-polluting industries are aligned with poorer and under-updated facilities. Three of the six facilities selected in this research are still operating according to older standards and have not experienced technical updates since 2005, whereas the downstream section has been actively promoted by government subsidies. This difference was not only shown in the location of facilities; it was more apparently expressed in the correlation of treatment methods with heavy metal co-existence as well. As filters with 0.5 mm diameter are applied as a traditional and less costly approach in filtering MP particles, the MPs in its sewage only showed approximately half the extent of correlation with heavy metal particles on average in

the 0.1 mm-diameter filtration facilities. It means that half the efficiency of heavy metal removal alongside MP removal. We can also see that, to maximize the utility of MP- heavy metal co-existence, wetland sedimentation, and WWTP filtration combined method, the latest approach mainly taken in downstream areas, surpasses filtration methods as it showed 0.36 in p. The findings generally prove earlier points on the co-existence of heavy metal and MPs in industrious area surface water conditions, while differences between the three sections are unexpectedly apparent.

Table 2. *Correlation of MP with heavy metal.*

Subject		Cu	Cd	Pb	Zn	Cr
Shapes	Fragment	0.61	0.43	0.51	ns	ns
	Film	ns	ns	ns	-0.46	ns
	Fiber	0.45	0.52	0.49	0.73	ns
Colors	Black	ns	ns	ns	ns	ns
	White	ns	ns	ns	ns	ns
	Transparent	0.41	0.39	0.39	ns	ns
	Multiple	0.62	0.51	0.67	ns	0.52
Sizes	Less than 0.5 mm	0.51	0.50	0.54	ns	0.41
	0.5 ~ 1 mm	ns	ns	ns	ns	ns
	1 ~ 2.5 mm	0.48	0.56	0.57	ns	0.55
	2.5 ~ 5 mm	0.40	0.39	0.45	ns	0.40
Chemical Materials	PE	0.55	ns	0.44	0.38	ns
	PP	ns	ns	ns	ns	-0.45

The level of co-existence of MPs and heavy metal with other pollutants can be explained in two approaches: the high adsorption and desorption capacities of the particles themselves through certain ecological, chemical, or physical mechanisms, or the domestic or industrious pollution that share a similar pattern with MP pollution in major cities.

Assuming that if specific MP characteristics showed a relatively high level of correlation with the absorption of other pollutants, the first hypothesis about co-existing mechanisms was worthy of closer analysis. Hence, we concluded the results in *Table 2*, where the correlation between MPs and heavy metals was analyzed from the aspects of morphology, color, particle size, and polymer component occurrence characteristics. Fragments and fibers were significantly correlated with Cu, Cd, Pb; colored and transparent MPs were significantly associated with large poly-metals; particle size ≤ 0. 5 mm and 1 ~ 5 mm MPs were significantly related to Cu, Cd, Pb, Cr; and polyethylene was significantly correlated with Cu, Pb and Zn.

A great public health hazard lies in MP's stimulation mechanism on heavy metals' transitions from non-effective states to effective states, which enlarges the threat heavy metals have on the aquatic ecosystem and industrious or residential use of surface water. Among the Yangtze River water body's physicochemical factors, key factors such as TOC, EC, pH, and sediment particle size contributed 33.7% to the change of heavy metal effective state ratio. Although the contribution rate of MPs alone is only 0. 7%, the synergistic contribution of the two reached 49. 6%.[30] These data suggested that MPs could further intensify the transformation of heavy metal forms to effective states and point to a deeper relation between MP occurrences with other water quality parameters.

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[30] Zhou X, Zhao Y, Pang G, et al. Microplastic abundance, characteristics and removal in large- scale multi-stage constructed wetlands for effluent polishing in northern China[J]. *Chemical Engineering Journal*, 2022,430:132752.

3.3. Fecal Indicators

To test if shared sources of MPs and sewage treatment contamination lead to their co-existence, we chose *E. coli* as a fecal indicator. We drew the Pearson correlation with MPs in these facilities with *E. coli* concentration in the same facilities. Surprisingly, the coefficient between MP concentration and *E. coli* is ranked as relatively low, with an average of 0.14, while in some facilities, typically downstream and in estuaries, the correlation is below zero, with some facilities providing a coefficient as low as -0.2. As the population of cities downstream of the Yangtze River surpasses the population upstream by more than three times, the correlation between fecal indicators and MP is weak.

3.4. Pharmaceutical and Chemical Personal Care Products and Antibiotics

Upon further exploring the relationship between MP distribution with human activities, we analyzed MP correlation with PPCPs and antibiotics, which are the most common contaminants in the Yangtze River and whose concentration and occurrence form were directly related to the sewage area's population, urbanization, and treatment methods, indicating possible relation with MP. According to *Table 1*, the Pearson correlation of MPs with PPCPs was high on average. From upstream to downstream, however, the coefficient started to decrease drastically, showing the weaker connection between MP particles with urbanization and domestic sewage pollution. Similar to what we have observed in MP's correlation with heavy metal, the reversed relation between urbanization extent and domestic pollutant occurrence could be explained by the second set of correlation analyses. While the advanced and updated facilities treating sewage from major industrious cities downstream were able to maintain a co-existence level as high as 0.56 and 0.70 in the final-stage sludge waste, their counterparts upstream with larger filtration gaps released more micro- or even nano-plastic beads into the river.
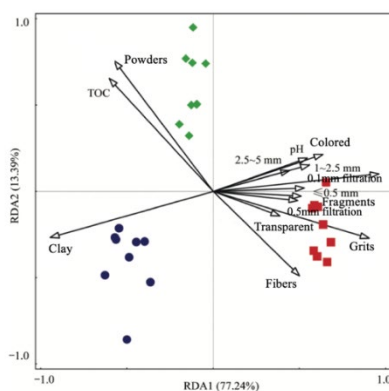
Figure 1. *Redundancy Analysis of MP-antibiotics occurrences.*

Assuming that mechanisms of MP-domestic pollutant coherence were consistent along the river, the lower co-existence meant more PPCP or antibiotic residue than the proportional amount that occurs alongside MP particles. To distinguish the effect of occurrence mechanisms with removal methods, we used

redundant analysis to point out the factors behind the p coefficient, as shown in *Figure 1*. It can be seen that color, particle size (≤0.5 mm, 1 ~ 5 mm), morphology (fragments, fibers), and polymer components (PE) were especially significant factors affecting the content of antibiotics. However, the difference between 0.5mm diameter filtration's influence on MP-antibiotic co-occurrence in tested sewage samples (indicated by the arrow) and 0.1mm diameter filtration was much larger than the minor difference between different shapes, sizes or chemical materials of MP particles. Thus, we concluded that the influence of MP-related co-existing mechanisms on the co-occurrence extent was larger than simply shared sources in urban pollution, while the difference in removal methods applied in facilities was an equally, if not more, significant variable.

3.5. Comparison in the Removal of MP-related Pollutants in WWTPs and CWs

According to the results of One-way ANOVA and following the Tukey post-hoc test, we found a statistically significant difference in average MP removal efficiency according to treatment type (F (2) =9.073, p < 0.001). A Tukey Post-hoc Test revealed significant pairwise differences between the combined treatment method and filtration through 0.1- mm filters, with an average difference of 0.42 pcs/L (p < 0.05). Between the combination method and filtration through 0.5-mm filters, with an average difference of 0.59 pcs/L (p < 0.01). This means that the constructed wetlands, regardless of their types or differences, performed better in removing MP particles than WWTP in most cases along the Yangtze River. However, as all combined treatment sites went through traditional filtration before treatment through wetlands, it is less convincing to claim any priority of CW mechanisms over traditional facilities. Yet, it is at least safe to say that CWs are highly effective in improving on the removal of pollutants, as they receive treated sewage from filtration processes and act as the final stage of effluent treatment before its entrance to the Yangtze.

4. Primary Data Analysis

## 4.1. MP Occurrences in Domestic Sewage WWTP1

4.1.1. Removal Efficiency
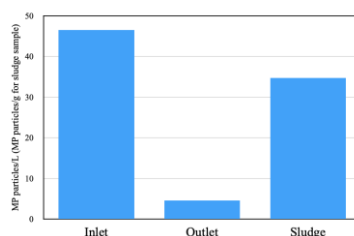
Figure 2. *MP concentration in WWTP1.*

The content of MPs in the influent water of the sewage treatment plant that treated domestic sewage is 46.5 pcs/L, a relatively small concentration compared to average data in similar facilities. It can also be seen that the concentration of MPs in the

discharged water of the sewage plant was 4.6 pcs/L, and the removal rate of MPs reached 90.1%. The total content of MPs in the sludge of the sewage plant was 34.7 pcs/g, which indicated that most of the MPs in the influent water would remain in the sludge. However, the content of MPs in the discharged water should not be underestimated, because the sewage plant had a large daily treatment capacity (treatment scale of 20,000 tons/day), and the amount of MP discharged into the ecological environment in the discharged water would consequently also be very considerable.

4.1.2. Particle Size Distribution

In this study, the particle size of the detected MPs was divided into three grades: 30.8~100 μm, 100~500 μm and 500~5000 μm. Most of the size of the wastewater-influent MPs in the sewage plant was distributed between 100-500 μm, followed by 30.8-100 μm (28%), and the smallest proportion was the part of MPs larger than 500 μm (6%). The largest proportion of effluent MPs in the size range, however, was between 100-500μm (46%), followed by 30.8-100μm (35%), while the size distribution range of MPs in sludge was relatively balanced between various size categories. These changes can be explained by the 0.1mm diameter filtration that is applied in the facility, as a decrease in the 63-125 μm category's proportion in the samples is observed.
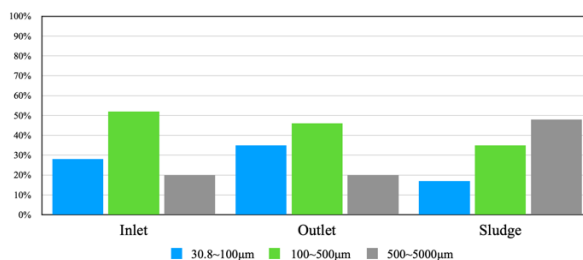

Figure 3. *MP Size distribution in WWTP1.*

4.1.3. Particle Shape Distribution

The MP shapes observed in this study included film, flakes, fragments, and fiber. Fragmented MPs accounted for about 49.8% of all particles observed samples, followed by fibrous MPs, accounting for 22.8%. The contents of film and flake-shaped MPs were small, accounting for 14.1% and 13.3%, respectively. The microscopic image of some representative MPs is shown in *Figure 5*.
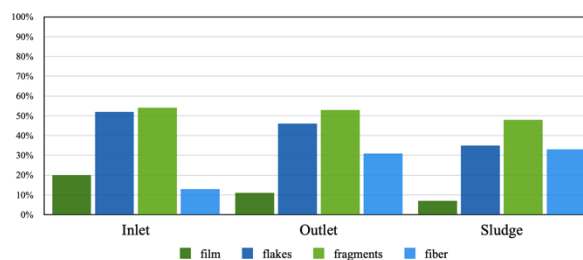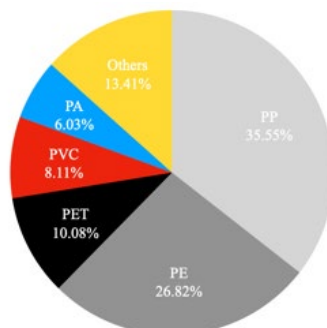

Figure 4. *MP shape distribution in WWTP1*
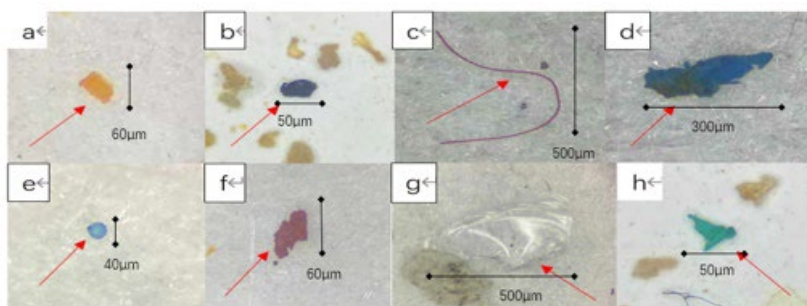
Figure 5. *Photos of MP particles under microscope. (a) yellow fragments, (b) black fragments, (c) red fibers, (d) blue fragments, (e) blue particles, (f) red fragments, (g) transparent films, (h) green fragments.*

4.1.4. Particle Chemical distribution

Figure 6. *MP chemical distribution in WWTP1.*

Among all the suspected MP particles observed, representative particles were randomly selected for identification and confirmation. A total of five polymer types were detected, including polyamide (PA), polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET), as shown in *Figure 6*. These detected polymers happened to be the main plastic polymer consumption types in China. [31] Among them, the main components of MPs are PP and PE, accounting for 35.55% and 26.82%, respectively. They were followed by PET and PVC, the least content component is PA, accounting for 6.03%, and other ingredients accounted for 13.41%.

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[31] Yin L, Wen X, Huang D, et al. Microplastics retention by reeds in freshwater environment[J]. *Science of The Total Environment*, 2021,790:148200.

4.2. MP Occurrences in CWs

4.2.1. Constructed Wetland Sampling

Table 3. *MP abundance, removal rate, and general water quality indicators in CW1.*

Site	Points	MP abundance (particles/L)	Removal Efficiency (%)	COD (mg/L)	TN (mg/L)	TP (mg/L)	TSS (mg/L)
CW1	A1	10.20±1.97	88.73 A1→A2	11.7±1.5	6.2±0.1	0.06±0.01	9.6±0.3
	A2	1.15±0.13	32.17 A2→A3	8.3±0.6	5.9±0.2	0.05±0.01	2.2±0.3
	A3	0.78±0.11	92.35 A1→A3	10.3±0.6	5.9±0.3	0.05±0.01	3.3±0.6

The abundance of MPs in sewage plant effluent can reflect the basic situation of the municipal drainage system, and the abundance of influent (sewage effluent) MPs (>30.8 μm) in CW1 is (10.20±1.97)/L. Past research data[32] show that the average MP abundance of sewage plant effluent was 6.99~17.2/L, which shows that the abundance of CW1 influent MPs was within the normal range, and most of the MPs in the raw sewage had been removed at the process end of the sewage treatment plant.

It can be seen from *Table 3* that, after the sewage passed through the vertical flow section of the wetland, the abundance of MPs decreased significantly to (1.15±0.13)/L, and the removal rates were 8.73%, similar to the results found by that of domestic and foreign scholars.[33] The undercurrent process section mainly removed MPs from sewage through the adsorption and filtration of the internal matrix, plant roots, and biofilm. When the effluent passed through the surface flow section of CW1, the abundance of MPs was further reduced to (0.78±0.11)/L, with removal rates of 32.17%, which were lower than the removal effect of the undercurrent process. This is because the surface flow process section mainly removed MPs in water through natural sedimentation, as well as the adsorption of some natural colloids— viscous suspended particles and plants.[34]

4.2.2. Particle Size Distribution

For CW1 inlet water, 100~500 μm MPs accounted for the largest proportion (57.8%), followed by 30.8~100 μm (29.1%) and 500~5000μm (13.1%). In the influent, the proportion of MPs with large particle size (500~5000 μm) was the least, similar to the results in the effluent of 7 sewage plants in Xiamen, a major southern coastal city in China.[35] In the effluent of CW1, the average proportion of MPs of 355~5000 μm in the effluent was 13.1%, and the proportion of MPs of 30.8~100 μm (small particle size) further increased, reaching 55.7%.

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[35] Long Z, Pan Z, Wang W, et al. Microplastic abundance, characteristics, and removal in wastewater treatment plants in a coastal city of China[J]. *Water Research*, 2019,155:255-265.
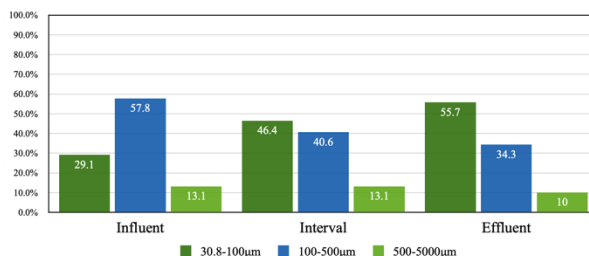
Figure 7. *MP size distribution in CW1.*

4.2.3. Particle Shape Distribution

As the sewage sources of CW1 included few domestic land uses, flake-shaped particles were detected less than 0.1%, so they are excluded from the following discussion. In the influent water of CW1, the proportions of fiber, fragments, and flakes were 65.1%, 19.9%, and 15.0%, respectively. The fiber accounted for the largest proportion of the effluent, which is consistent with the results of previous studies.[36] In the effluent of CW1, fibers, chips, and flakes accounted for 80%, 17.1%, and 2.9%, respectively. In contrast, the proportion of fiber-shaped MPs from inlet to outlet increased significantly, indicating that fibers were the most difficult to remove among the three shapes listed.
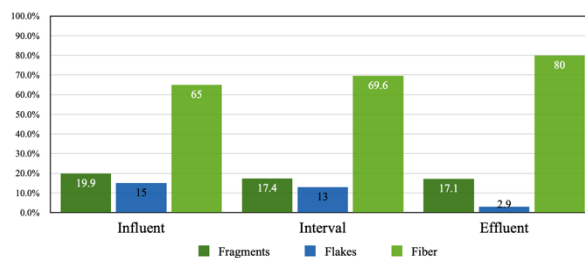
Figure 8. *MP shape distribution in CW1.*

4.2.4. Particle Chemical Distribution

Due to an identical reason in the difference of MP sources in sewages, data from CW1 presents a replacement for polystyrene (PS). In the influent water, the proportions of PP, PE, PS, and PET-type MPs were 12.1%, 6.9%, 28.1%, and 52.9%, respectively. In CW1 effluent, PP, PE, PS, and PET type MPs accounted for 21.4%, 4.3%, 17.1%, and 57.1%. The proportion of PET-type MPs increased compared to the inlet data because fiber-shaped MPs are mainly PET-type.

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[36] Mahon A. M., O'Connell B., Healy M. G., et al. Microplastics in sewage sludge: Effects of treatment [J]. *Environmental Science & Technology*, 2017, 51(2), 810-818.
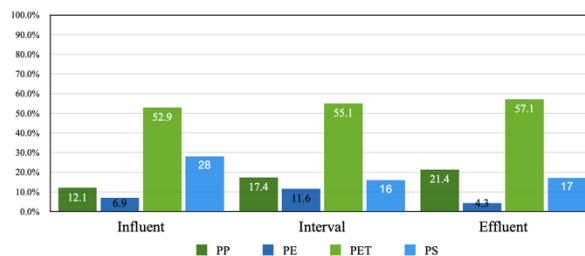
Figure 9. *MP chemical distribution in CW1.*

4.4. Comparing MP-related parameters between two methods

Overall, CW1 removed MPs at a slightly higher rate (92.35%) than WWTP1 (90.1%). The presence of large amounts of floating plants and algae in the water (*Figure 10*) could effectively intercept and settle MPs before they flow out of the wetland, enabling wetlands with a more flexible approach to filter the particles through complex stages of sedimentation around roots of plants and coherence with microorganisms.

Figure 10. *Plants in CW1.*

Regarding particle sizes, both sides showed a positive correlation between increasing removal rate with particle sizes, yet the removal rate of smaller particles less than 500 μm was higher in WWTP1 than CW1. MPs with large particle sizes were more easily removed in the sewage treatment process. [37] Some research results suggested that small-sized MPs are more likely to escape the capture of constructed wetland substrates and that large-sized MPs will gradually decompose with sewage flow, forming small-sized MPs, [38] which is the main reason for their higher concentration detected in the CW. This, unfortunately, leads to a fallback of CWs, as *Table 3* and *Figure 1* have shown in the secondary analysis that the smaller MP particles are, the stronger their co-occurrence with heavy metals (especially Cu) and PPCPs are in effluents.

As for shape distribution in the analysis, while both WWTP1 and CW1 removed flakes and films effectively, WWTPs showed a statically significantly lower efficiency in removing fragments than the CW, yet, both methods performed poorly

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[37] Wang Q, Hernández-Crespo C, Du B, et al. Fate and removal of microplastics in unplanted lab-scale vertical flow constructed wetlands[J]. *Science of The Total Environment*, 2021,778:146152.

[38] Liu W, Zhang J, Liu H, et al. A review of the removal of microplastics in global wastewater treatment plants: Characteristics and mechanisms[J]. *Environment International*, 2021,146:106277.

in removing fibers. In a study done in a similar CW environment,[39] the removal rate of vertical flow constructed wetlands for other shapes of MPs was about 95%, while the removal rate of fiber-shaped MPs was only 81%, which largely matches the results of this study. Fiber-shaped MPs have a large aspect ratio and smooth surface and easily pass longitudinally through porous media under the action of water flow, which may be the main reason why they are more difficult to remove than other shapes.[40] However, their relation to environmental hazards is lower than that of fragments, whose irregular surface attracts pollutants to form co-occurrences.[41] Thus, from an ecological perspective, CWs are more capable of lowering MPs' ecological hazard in aquatic ecosystems along the Yangtze River.

Regarding the chemical material distribution, CWs performed better than WWTPs in treating PE and PP particles, whereas PET was removed more thoroughly in WWTPs. The reason might be that a large number of fiber-shaped MPs were detected as PET type because PET type plastics are the main material of home textile clothing. This further proves that the plastic microfibers released by people during the laundry process are the main source of MPs in sewage plants.[42] It is also worth noticing that during field sampling of CW1, it was found that on-site workers were using green nylon strings to bind boats on the surface of the surface of the constructed wetland to secure the surface flow, which may be the source of PA-type MPs.

5. Discussion

5.1. Comparison to Previous Work

While this research showed coherence within the fields of MP sourcing, co-existence and removal, CW treatment mechanisms and efficiency, and MP-related pollution occurrences in wetlands, it bore diverse levels of differences and offered innovative approaches.

As noticed, this research has cited multiple research about MP particles: particularly their general description, co-existence with heavy metals, organic compounds, and fecal contamination in surface water and their sources in human activities. As a result, similarities in the introduction to the basic parameters and characteristics of MPs and listed references are possible. Additionally, this research shared similar correlation methods in analyzing occurrence data collected from water treatment facilities with previous studies[43]. However, we presented the correlation of MP and other pollutants and offered field sampling results to further test the assumptions and came to our conclusions. Our research also covers a range of various locations along the Yangtze River which increased the credibility of our data analysis,

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[39] Wang Z, Sedighi M, Lea-Langton A. Filtration of microplastic spheres by biochar: removal efficiency and immobilisation mechanisms[J]. *Water Research*, 2020,184:116165.

[40] Raju S, Carbery M, Kuttykattil A, et al. Transport and fate of microplastics in wastewater treatment plants: implications to environmental health[J]. *Reviews in environmental science and biotechnology*, 2018,17(4):637-653.

[41] Wang J, Zheng L, Li J. A critical review on the sources and instruments of marine microplastics and prospects on the relevant management in China[J]. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 2018,36(10):898-911.

[42] Gaylarde C, Baptista-Neto J, Da Fonseca E. Plastic microfibre pollution: how important is clothes' laundering?[J]. *Heliyon*, 2021,7(5):e7105.

[43] Lares M, Ncibi M C, Sillanpää M, et al. Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology[J]. *Water Research*, 2018,133:236-246.

while previous studies mostly focus on limited geological locations[44].

We observed other differences between our methodology with previous works in the same field. Many previous researchers more closely studied the characteristics of MPs and how they affected the removal mechanisms,[45] while we based our initial point on their work and conclude the applications and influences that these phenomena present to the overall water quality in the area.

5.2. Limitations

The most obvious limitation of this paper is undoubtedly the lack of comprehensive parallel analysis between different wetland treatment mechanisms, or even among the same mechanisms. While CW1 in this paper combines the vertical flow section with the surface flow section to maximize the removal rate, there are currently three main types of wetland mechanisms contributing to Yangtze River water treatment. In horizontal undercurrent wetlands, the third type, sewage treatment is degraded by organic matter through aerobic areas (plant root zones) and anoxic areas, and studies have shown that these wetlands can effectively remove pollutants such as BOD, COD, ammonia, nitrogen, phosphate, and suspended solids particles from sewage. As mentioned in the introduction, the complex interaction between various vegetation (regarding the various climate or geographical conditions along the river) and similarly diverse co-existing pollutants requires long-term, thorough, and localized research. However, due to the relatively short amount of time, relatively long distances, and geographical obstacles for this research, we failed to include this type of wetland in the scope of analysis. Similarly, as the usage of riverside wetlands is diverse from targeted industrious chemical wastewater treatment to small-scale aqua-agriculture fields, numerous possibilities exist in the combination of different mechanisms along the Yangtze. With our limited scope on only one vertical-surface flow CW in Nanjing, regardless of how typical the mechanism is, reliability is lowered by the extraordinary diversity in water quality and treatment along the Yangtze River.

Another critical limitation of the paper is the inability to relate the respective data of the same parameters in the WWTP and the CW with their geological locations. For instance, if they were less than 10 kilometers apart along the river and the concentration of MP particles was irregular debris, because these shapes are most commonly detected in either aging daily use of plastic products or personal care products such as toothpaste, we could safely come to a reasonable assumption of the sources of MPs in one daily care chemical product factory sewages. However, the two sites bear a direct distance of 30 km and an actual water-flow distance of 55 km. So, such reasoning that detects the sources of contaminants is too vague to possibly be reliable with merely non-pointed source assumptions based on previous research and less solid proof for any sourcing methods applied.

5.3. Implication for Research, Policies, and Practices

The chart in the secondary data analysis lists all current studies on the occurrences and removal of MP particles in CWs and saves time and resources for future research in directing peer reviews or developing more advanced perspectives based on the overall critical analysis of the previous studies. Similarly, our methodology helps

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[44] Kooi M, Besseling E, Kroeze C, et al. Erratum to: modeling the fate and transport of plastic debris in freshwaters: Review and guidance[M]Springer, 2018.

[45] Wang Z, Sedighi M, Lea-Langton A. Filtration of microplastic spheres by biochar: removal efficiency and immobilisation mechanisms[J]. *Water Research*, 2020,184:116165.

researchers who aim at other parts of the world to sample surface waters and analyze their collected results by replicating these same procedures.

The co-existence between MP and heavy metal and the patterns in their occurrence in WWTP1 and CW1 proved in the paper is crucial for further developments in wastewater treatment. If further improvements on the construction and maintenance of these facilities are better informed about increasing contamination of the MPs, the efficiency in treatment and protective impacts on the local environment is likely to increase through shifting to more energy-saving, eco-friendly, and efficient engineering planning, as well as more timely processing or more comprehensive cleaning operations that lessens environmental self-cleaning stress that wetlands face. Policies also benefit hugely from the result of our analysis on the sources of MPs in treatment plantations. By offering subsidies only to the most promising industries or products that end up producing the least waste into surface water and require merely the most economical and common treatment plants. On the other hand, our conclusions on the most efficient treatment approaches in diverse circumstances almost directly serve for policy-making and commercial investment in the construction of treatment facilities around surface waters where different usages are needed.

Generally, all methods and results in this paper are available for both reference and citation, which directly assists further upstream or downstream publications. Critical opinions point out problems or fallbacks that remind future researchers of highly possible problems, indirectly contributing to the overall academic development.

5.4. Future Directions

According to our original research plan, the next step is to include primary data analysis on the removal rate, sizes, colors, and shapes of MPs and other basic water quality parameters (turbidity, BOD, heavy metal, etc.) of a typical horizontal undercurrent wetland along the Yangtze River. Then, a complete chart of the MP removal efficiency and treatment mechanisms in these three major types of CW should be drawn. With basic physical or chemical parameters of the sewage as factors, the chart should give out the most suitable type of treatment to remove MPs and related contamination thoroughly. Based on this chart, software should be built to build models to simulate treatment processes and calculate the efficiency based on the formulas, giving suggestions on future construction and maintenance.

It is also important that a globally unified unit of calculating MP concentration and categorizing particles' sizes be applied in related research. At present, there is no unified expression of MP content; commonly used units include the number or weight of MPs per unit area or unit volume of sample, and the number or weight of MPs per unit mass sample, which limits the comparison of MP content between different research reports. In addition, the diverse methods in the categorization of MP particles in terms of size interfere with common infiltration filters produced globally regarding a fixed standard, which would significantly improve the regulation of MP in global water treatment. Similar problems are affecting wetland regulation as well. As wetlands are complicated structures that involve different mechanisms and components, categorization methods and statistics of wetland treatment removal rates are chaotic. To solve these problems, further discussion on both MP calculation standards and wetland regulation is in urgent need.

Acknowledgement

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Transformations of the Great Mosque of Cordoba: Deciphering Political and Religious Messages in Medieval Spain

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Abstract

This paper explores how the continual transformations of the Great Mosque of Cordoba in Medieval Spain have conveyed specific political and religious messages utilized by the Umayyad dynasty to strengthen its rulership. As an architectural monument characteristic of al-Andalus, the Great Mosque of Cordoba is subject to a debate on its pre-Islamic origin and has been incorporated into a historical narration glorifying the Islamic triumph over Christianity and the dynastic legitimacy and political might of the ruling Umayyads. By analyzing the mosque's construction under Abd al-Rahman I in the late eighth century and its successive expansions from the ninth to the late tenth century, the study interprets the building as the setting for dynastic disputes, religious confrontations, and diplomatic exchanges. The paper argues that the complex Medieval meanings of the mosque have culminated in an enduring legacy that continues to play a significant role in the religious and political dynamics in Spain, even after the Reconquista and in modern Spanish society.

Introduction

Medieval Spain is characterized by complex geopolitical contacts between rival powers and religious interactions between Islam and Christianity. Once ruled by the Visigoths, a group of Germanic people that succeeded the Western Roman Empire, from the fifth century onwards, Spain was conquered by the Umayyad Caliphate, the dominant Islamic power based in Damascus, between 711 AD and the 780s AD.[1] After capturing the city of Cordoba, the heir to the Umayyad dynasty, Prince Abd al-Rahman I, established the Emirate of Cordoba in 756,[2] which was proclaimed the Caliphate of Cordoba under Abd al-Rahman III in 929. Following a period of political strife in the early eleventh century, the once-powerful caliphate

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[1] "The Visigothic Kingdom," Encyclopædia Britannica, June 12, 2023, https://www.britannica.com/place/Spain/The-Visigothic-kingdom; "Muslim Spain," Encyclopædia Britannica, June 12, 2023, https://www.britannica.com/place/Spain/Muslim-Spain.

[2] Editors of Encyclopædia Britannica, "ʿAbd Al-Raḥmān I," Encyclopædia Britannica, July 20, 1998, https://www.britannica.com/biography/Abd-al-Rahman-I.

disintegrated into numerous independent kingdoms. [3] What ensued were the Christian campaigns in the Reconquista that swept across the Iberian Peninsula, which led to the downfall of the last Islamic kingdom in Spain in 1492. [4]

As a paradigm of Medieval Spanish architecture, the fate of the Great Mosque of Cordoba (Fig. 1) is interwoven with the shifting political and religious circumstances of the era. Believed to be preceded on the site by the Basilica of Saint Vincent in the Visigothic Kingdom of Spain, the congregational mosque was commissioned by Abd al-Rahman I in 785 and became a ceremonious symbol of the new Emirate of Cordoba. [5] Subsequent Umayyad rulers, from Abd al-Rahman II in the early ninth century to Hisham II in the late tenth century, made successive expansions to the mosque, transforming it from five or six thousand square meters into the third largest mosque in the entire Islamic world, measuring over twenty thousand square meters. [6] In 1236, after the Christian capture of the city of Cordoba, the mosque was reconsecrated as the Catedral de Santa Maria. [7] In the present day, the building remains under the ownership of the Catholic Church, though it has become a central issue in modern Spanish politics just as it was in Medieval Spain.

Whether in the Middle Ages or the contemporary era, the continuous transformations of the Great Mosque of Cordoba contribute to its profound and enigmatic identity. In order to understand the role of the mosque as an architectural monument shared by both Muslims and Christians in the past and present, it is necessary to interpret the rich messages that it carries throughout its transformations. This paper seeks to investigate the political and religious meanings of the Great Mosque of Cordoba under Umayyad expansions by analyzing the building as the setting for dynastic disputes, religious confrontations, and diplomatic exchanges. By demonstrating how the Umayyads constructed the mosque as a symbol of imperial strength, religious triumph, and dynastic legitimacy, this paper contends that, even after the Reconquista and in Spanish society today, the complex Medieval meanings of the mosque have become an enduring message in an ever-changing world.

Pre-Islamic Origins and a Purposeful Narrative

In 750, the Umayyad Caliphate was overthrown by the Abbasid Revolution, and Abd al-Rahman I was one of the few surviving members of the Umayyad royal family. After fleeing to North Africa, he arrived in Cordoba and established a new emirate in 756 as a continuation of the Umayyad dynasty. Thirty years later, in 785, Abd al-Rahman I commissioned the Great Mosque of Cordoba, which was completed in one year (Fig. 2). [8] While no Umayyad sources fully discuss the site's earlier history, some clearly described the mosque's construction; among them are the accounts of the faqih Muhammad ibn 'Isa from the eighth century and of al-Razi from the tenth century. Although no written texts by the two historians survive, the thirteenth-

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[3] Editors of Encyclopædia Britannica, "Caliphate of Cordoba," Encyclopædia Britannica, July 19, 2019, https://www.britannica.com/place/Caliphate-of-Cordoba.

[4] Editors of Encyclopædia Britannica, "Reconquista," Encyclopædia Britannica, May 5, 2023, https://www.britannica.com/event/Reconquista.

[5] Jerrilynn D. Dodds, "The Great Mosque of Córdoba," in *Al-Andalus: The Art of Islamic Spain* (New York: The Metropolitan Museum of Art, 1992), 12.

[6] Jonathan M. Bloom, "Rival Caliphates in the West during the Tenth Century," in *Architecture of the Islamic West* (New Haven: Yale University Press, 2020), 78.

[7] Heather Ecker, "The Great Mosque of Córdoba in the Twelfth and Thirteenth Centuries," *Muqarnas* 20 (2003): 117.

[8] Dodds, "The Great Mosque of Córdoba," 12.

century historian Ibn 'Idhari cited them in his *Al-Bayan al-Mughrib*, a book on the history of the Maghreb and al-Andalus.[9] He wrote,

> When the Muslims conquered al-Andalus … they expropriated from Christians who had capitulated on terms half of every church which the Christians owned, such as, for example, the church of Damascus and others. In like fashion, the Muslims expropriated from the Mozarabs[10] half of the main church, within the walls of Cordoba, and built on that half a great mosque, leaving the other half in the hands of the Christians, whose remaining churches were destroyed … But when the number of Muslims in al-Andalus multiplied and Cordoba flourished, and when the Arab princes with their armies took up residence in the city, that mosque was no longer big enough for them … When Abd al-Rahman ibn Mu'awiya arrived in al-Andalus and took up residence in Cordoba, he turned his attention to the matter of the great mosque, seeing to its enlargement and the completion of its construction. He summoned to his presence the Mozarabs of Córdoba and requested that they sell the part of the aforementioned church that they still owned … Thus the Christians gave up their part of the building, which the emir incorporated into the Great Mosque. Abd al-Rahman al-Dakhil commenced the demolition of the church and the construction of the Great Mosque in the year 169. Its construction, once the naves were in place and its walls closed, was completed in the year 170—all in the space of a single year. It is said that the sum that Abd al-Rahman spent on the construction of the Great Mosque was 80,000 coins of good weight.[11]

The seventeenth-century historian Ahmad al-Maqqari, also writing on the demolition of a preceding church and the construction of a new mosque, stated,

> He summoned the most important men among the Christians and demanded the sale of the part of the church that they still owned, which abut- ted the great mosque, in order to be able to incorporate that part into the mosque, offering to remunerate them splendidly for it in accordance with the terms of the pact under which the Christians had originally capitulated. At first they refused to sell what belonged to them. However, after much entreaty, they gave in, requesting that they should be allowed to rebuild those churches outside of the walled town which had been demolished. They then turned over to the Muslims the half that had been asked of them. Thus the matter came to an end, in the year 168. Then Abd al-Rahman built the great mosque in the form which the author describes.[12]

According to these narrations, local Muslims and Christians once shared a church that predated the Umayyad mosque. As the Muslim population of Cordoba

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[9] Manuel Ocaña Jiménez, "The Basilica of San Vicente and the Great Mosque of Córdoba," in *The Formation of Al-Andalus, Part 2*, 1st ed. (Abingdon-on-Thames: Routledge, 1998), 264.

[10] The term "Mozarabs" refers to the Christians living in al-Andalus after the Umayyad conquest in the eighth century.

[11] Ibn 'Idhari, *Bayān*, vol. 2, trans. Edmond Fagnan (Algiers: Imprimerie Orientale P. Fontana, 1901-4), 378, quoted in Manuel Ocaña Jiménez, "The Basilica of San Vicente and the Great Mosque of Córdoba," in *The Formation of Al-Andalus, Part 2*, 1st ed. (Abingdon-on-Thames: Routledge, 1998), 261-262.

[12] Ibn 'Idhari, *Bayān*, vol. 2, trans. Fagnan, 368, quoted in Jiménez, "The Basilica of San Vicente and the Great Mosque of Córdoba," 264.

increased, the building was no longer large enough for the Muslim congregation. It was purchased by Abd al-Rahman I, who then demolished the structure to construct a new mosque. Though the Muslim chronicles did not mention the name of the church, it was no doubt the Basilica of Saint Vincent; modern archaeological excavations substantiate its existence (Fig. 3).[13]

The commonly accepted account of the relationship between the mosque and the basilica is not entirely credible, though. As Manuel Ocaña Jiménez's interpretation of these historical texts suggests, the Umayyads claim to have constructed a completely new building on the site, but the physical evidence suggests otherwise. Rather, the Umayyads established a narrative on the erection of a new mosque to signal their political and religious predominance over their Christian predecessors. In particular, the church's destruction and its ultimate replacement by a congregational mosque epitomize the triumph of Islam over Christianity, not in a barbarous way but through entirely legitimate negotiations. The event, with its glory and pride, also fits in a tale of conquest—whether that is the capture of Visigothic Cordoba by Muslims in 711 or Abd al-Rahman I's defeat of Yusuf al-Fihri, the then-governor of al-Andalus, in the struggle for rulership in Cordoba in 756. The parallel drawn between the church of Saint Vincent and Saint John in Damascus in Ibn 'Idhari's account was also intended to elevate the Umayyads' prestige. Just as how the Umayyad caliph al-Walid I was willing to share the sacred space with Christians in Damascus, the Umayyads of Cordoba at first also tolerated their Christian subjects to worship in the same space as they did, though they eventually purchased the church and reconstructed it as a mosque. The traditional Umayyad account, passed down from Muhammad ibn 'Isa to Ibn 'Idhari, thus subtly portrayed the religious magnanimity of the Spanish Umayyads, embellishing their religious triumph with honor.[14]

The origin of the Great Mosque, some scholars believe, can possibly be traced back to the pre-Islamic era of Spain, when it was settled by the Phoenicians from the twelfth to sixth century BC.[15] Located on the bank of the Guadalquivir River, the Phoenician structure that predated the mosque could have functioned as a warehouse or an observatory. It is known that the Phoenicians established trading networks with the Tartessians in the Iberian Peninsula; therefore, a commercial center near the river would have created a strategic setting for transporting Tartessian goods on the waterway. This would have been especially favorable for securing the trade route from along the Guadalquivir River, which eventually led to the Gulf of Cadiz.[16]

The Romans conquered Cordoba in the second century BC and established a colony, Colonia Patricia, between 46 and 45 BC.[17] At this point, they likely

[13] D. Fairchild Ruggles, "The Stratigraphy of Forgetting: The Great Mosque of Cordoba and Its Contested Legacy," in *Contested Cultural Heritage*, ed. Helaine Silverman (New York: Springer, 2011), 56.

[14] Manuel Ocaña Jiménez, "The Basilica of San Vicente and the Great Mosque of Córdoba: A New Look at the Sources," in *The Formation of Al-Andalus, Part 2*, 1st ed. (Abingdon-on-Thames: Routledge, 1998), 265.

[15] Marvin H. Mills, "The Pre-Islamic Provenance of the Mosque of Cordoba," *Al-Masāq* 4, no. 1 (1991): 1, https://doi.org/10.1080/09503119108576977.

[16] Marvin H. Mills, "Phoenician Origins of the Mosque of Cordoba, Madina Azahara and the Alhambra," in *Across the Mediterranean frontiers: trade, politics and religion, 650-1450: selected proceedings of the International Medieval Congress, University of Leeds, 10-13 July 1995, 8-11 July 1996*, eds. Dionisius A. Algius, Ian Richard Netton (Turnhout: Brepols, 1997), 49.

[17] John Pollini, *From Republic to Empire: Rhetoric, Religion, and Power in the Visual Culture of Ancient Rome* (Norman: University of Oklahoma Press, 2012), 531.

renovated the preexisting Phoenician structure and adapted it for other purposes.[18] Modern excavations of the remains of the Roman city of Cordoba demonstrate that the Great Mosque of Cordoba was aligned with the street plan of Colonia Patricia, which provide a possible explanation for the mosque's disputable orientation; contrary to most other mosques in al-Andalus, the Great Mosque of Cordoba does not face Mecca. Instead of orienting twelve degrees south of east, in the direction of Mecca from Cordoba, the mosque orients sixty degrees south of east. This happened because the mosque followed the solstitial alignment of the Roman street plan. The Romans based their city on astronomical directions so that its minor axis corresponds to the solstitial axis formed by summer sunrise and winter sunset.[19]

The question remains as to why the Umayyads did not adjust the building's orientation but retained its original layout. One possibility is that the Muslims actually considered the orientation to be justifiable. Perhaps coincidentally, the Kaaba also has a minor axis that parallels the solstitial axis connecting summer sunrise and winter sunset, just as the street plan of Colonia Patricia and the Great Mosque. In this way, although the mosque does not face Mecca, it does face the Kaaba, and thus its orientation was perceived to be appropriate for prayers.[20] However, even as historical sources suggest that the qibla orientation had a solid astronomical basis, it was still a matter of controversy. When the Umayyads expanded the mosque in the tenth century, there was a debate on whether the qibla orientation should be altered. The historian al-Maqqari wrote from the seventeenth century that astronomers suggested reorienting the qibla of the Great Mosque of Cordoba following the model of the Great Mosque of Madinat al-Zahra, another mosque near Cordoba. Al-Hakam II, the Umayyad caliph, was ultimately convinced that maintaining the original qibla orientation signifies the continuation of ancestral traditions and decided to not change it.[21] The episode testifies to the prolonged influence of the urbanism of Roman Cordoba on the mosque, whether the Umayyads accepted it consciously or unconsciously. While later caliphs regarded the exceptional qibla orientation as a persistent Umayyad tradition, it was nevertheless a pre-Islamic attribute.

From the sixth to the seventh century, the Visigoths captured Cordoba from the Romans and consecrated the Basilica of Saint Vincent, on the remains of which the Umayyad mosque was later constructed. However, Ibn 'Idhari's narration of the Visigothic basilica and Abd al-Rahman I's new mosque is largely questionable. As he recorded, the new mosque was completed in a single year, from 785 to 786.[22] It is unlikely that an entirely new structure was built in such a short length of time given that later expansions generally took several years or even over a decade.[23] Rather than totally demolishing the basilica and erecting a new structure, the Umayyads retained the foundation of the preexisting basilica and adopted it as part of their new mosque. This explains why the Umayyad mosque inherited certain pre-Islamic features, particularly its layout and qibla orientation. If the mosque was a new Umayyad construction from the very beginning, these traits would likely have been

[18] Mills, "Phoenician Origins of the Mosque of Cordoba, Madina Azahara and the Alhambra," 47.

[19] David A. King, "The Enigmatic Orientation of the Great Mosque of Córdoba," *Suhayl. International Journal for the History of the Exact and Natural Sciences in Islamic Civilisation*, no. 16-17 (2019): 48-50, https://doi.org/10.1344/SUHAYL2019.16-17.2.

[20] King. "The Enigmatic Orientation of the Great Mosque of Córdoba." 59-61.

[21] Nuha N. N. Khoury, "The Meaning of the Great Mosque of Cordoba in the Tenth Century," *Muqarnas* 13 (1996): 83, https://doi.org/10.2307/1523253.

[22] Ibn 'Idhari, *Bayān*, 2, trans. Fagnan, 378, quoted in Jiménez, "The Basilica of San Vicente and the Great Mosque of Córdoba," 262.

[23] Marvin H. Mills, "The Pre-Islamic Provenance of the Mosque of Cordoba," 5.

discarded.

What these pieces of evidence illustrate is that the actual condition of the Great Mosque of Cordoba after Abd al-Rahman I's construction was not consistent with the descriptions provided by Umayyad chronicles. By describing how the caliph demolished a basilica and erected a new mosque, historians such as Ibn 'Idhari portrayed the Umayyads as who cleansed Cordoba of its Christian past and successfully established a new Islamic regime. Their political narrative, however, presented facts misleadingly. The Islamic identity of the mosque was never as pronounced as what the historians professed, since it reused the pre-Islamic architectural foundations. The sense of religious triumph that the Umayyad accounts exhibit is disputable; the mosque, after all, was not a complete Islamic triumph.

The political message of the mosque, regardless of its credibility, was precisely what the Umayyads needed in the late eighth century. Built thirty years after the Emirate of Cordoba was born, the mosque became a powerful means for the rulers to display their strength to the local Spanish population. While it may have been financially difficult for Abd al-Rahman I to erect an entirely new mosque, the very concept of a new congregational mosque was sufficient to symbolize political and religious hegemony in a newly conquered Islamic territory. This was precisely what later Umayyad historians sought to accomplish.

Abd al-Rahman I and II: Legitimization of the New Emirate

The foundational mosque commissioned by Abd al-Rahman I in 785, despite the persistence of its pre-Islamic identity, was a conscious effort to connect the new Emirate of Cordoba with the past to legitimize political powers. The plan of the mosque resembled a square with each side length being approximately seventy-nine meters. It consisted of a walled courtyard to the south and a hypostyle hall, divided into eleven aisles of twelve bays, to the north (Fig. 1).[24] The hypostyle hall (Fig. 4), perpendicular to the qibla wall, was designed to support large prayer gatherings and provide separate spaces for worshippers, which followed the conventions of other mosques—a typical example is the Al-Aqsa Mosque in Jerusalem, built by the Umayyads in the late seventh or early eighth century.[25]

One of the striking features of the hypostyle hall is the double-tiered horseshoe arches with voussoirs of alternating red bricks and white stones. The arcades, with their extraordinary degree of intricacy, lack direct precedents, but the techniques can be traced to the earlier architecture of the Iberian Peninsula. For instance, they may have been an emulation of the Roman aqueduct at Merida, which adopted multiple tiers of arches using brick and stone masonry. The horseshoe arches, likewise, were a prevalent element in both Visigothic churches and Muslim structures in Spain before the arrival of Abd al-Rahman I. They were found, for example, on the portal of San Juan Bautista de Baños de Cerrato (Fig. 5), a seventh-century Visigothic church. The series of arches likely drew parallels to the Great Mosque of Damascus (Fig. 6), which similarly had a courtyard surrounded by two levels of arcades and was built when the Caliphate of Umayyad was at the height of its power.[26] Given the strong link with both the Spanish and Syrian architectural traditions, the arcades were not merely devised to raise the height of the structure but were a purposeful appropriation. For Abd al-Rahman I, the heir to the now-

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[24] Dodds, "The Great Mosque of Córdoba," 12.
[25] Dodds, "The Great Mosque of Córdoba," 15.
[26] Dodds, "The Great Mosque of Córdoba," 15.

vanished Umayyad dynasty who had escaped to the foreign land of al-Andalus, the mosque permitted him to solidify the authority of his emirate with reference to historical foundations and to express nostalgia for his former homeland. The adoption of indigenous elements, whether Muslim or pre-Muslim, helped establish the connections between the Umayyads and Spain and produced a composite Hispano-Umayyad style.

The use of spolia in Abd al-Rahman I's construction provides another conspicuous example of the mosque's dialogue with the past. Roman and Visigothic shafts and capitals (Fig. 7) were positioned in pairs in the central aisle, forming a visually distinct passageway that led to the mihrab. As the central aisle was where the emir would walk through, the arrangement reconstructed the celebration of Roman triumphs.[27] On the one hand, it elevated the political status of the Umayyads to that of the Romans, ornamenting the emirate with historic glories. On the other hand, it signified the ascendency of the Umayyads over their Andalusian predecessor, resembling an exhibition of spoils of war. The spolia also implied that the Muslims were not barbaric and destructive conquerors but were illustrious victors who respected history while taking pride in it.

The expansions of Abd al-Rahman II again embraced the use of Classical capitals and shafts. Between 833 and 848, Abd al-Rahman II demolished the former qibla wall and the mihrab, extending the hypostyle hall 8 bays to the south.[28] He placed, for example, a pair of Visigothic shafts at the south end of the extended central aisle, delineating a rectangular space in front of the mihrab. However, there is evidence suggesting that apart from employing spolia, he also commissioned new capitals. The Corinthian shafts and capitals on the mihrab (Fig. 8), which date back to the ninth century and were relocated in the tenth century, were stylistically Byzantine but perhaps not entirely of Byzantine origin; the capitals were likely fashioned in Muslim workshops.[29] The use of spolia was discontinued, though, in the additions made after Abd al-Rahman II. Instead, craftsmen carved decorative elements in imitation of spolia, so that the carvings could be designed for specific architectural spaces. The practice was not only seen in the Great Mosque of Cordoba but also elsewhere in Umayyad Spain. The capitals from the Aljama Mosque in Madinat al-Zahra, built by Abd al-Rahman III in the 940s, were entirely produced by Muslim artisans, who not only emulated Visigothic carvings but also incorporated Umayyad imaginations into their works. [30] The shift from utilizing spolia to reproducing spolia does not diminish the roles of ancient fragments in the early stage of the mosque's construction. Rather, it reflects a strong interest of the Umayyads in reviving Classical forms and appropriating their political implications. The primary purpose of using spolia was not pragmatism in the process of construction but the affirmation of the Umayyads as the legitimate heir to the Greek, Roman, and Visigothic legacies.

[27] Carmen González Gutiérrez, "Spolia and Umayyad Mosques: Examples and Meanings in Córdoba and Madinat al-Zahra'," *Journal of Islamic Archaeology* 9, no. 1 (September 2022): 88, https://doi.org/10.1558/jia.23646.

[28] Dodds, "The Great Mosque of Córdoba," 15.

[29] González Gutiérrez, "Spolia and Umayyad Mosques: Examples and Meanings in Córdoba and Madinat al-Zahra'," 88-89.

[30] González Gutiérrez, "Spolia and Umayyad Mosques: Examples and Meanings in Córdoba and Madinat al-Zahra'," 95.

Abd al-Rahman III and al-Hakam II: Affirmation of the Umayyad Identity in Political Rivalries

The tenth century was characterized by the rivalry between Islamic caliphates, beginning with the establishment of the Fatimid Shi'i Caliphate in 909, which challenged the political and religious authority of the Abbasid Caliphate (Fig. 9). Abd al-Rahman III, exploiting the opportunity, subsequently proclaimed himself as the caliph of Cordoba in 929.[31] He began constructing a new capital, Madinat al-Zahra (Fig. 10), near Cordoba in 936, the architecture of which inherited the style of horseshoe arches with alternating voussoirs from the Great Mosque of Cordoba as the distinctive visual identity of the Umayyads. In a short time, he began expanding the Great Mosque (Fig. 11) itself as part of the manifestation of his political ambitions. In 951, the courtyard was renovated and expanded to a slight extent to the north, and its piers and columns formed a gallery similar to that of the Great Mosque of Damascus (Fig. 12). By 958, a new minaret with a height of forty-seven meters was completed beside the entrance to the courtyard, replacing an earlier short tower built by Hisham I.[32]

There were two staircases inside the square minaret, lit by light penetrating through the arched windows on the exterior. The staircases led to a balustraded platform, on which sat a chamber decorated with gold and silver balls on the top. The remarkable fact about this addition is that minarets were not part of the established traditions of mosques in al-Andalus at the time. Abd al-Rahman III's minaret carried a ceremonious function as it issued calls for prayers and, with its exceptional height, served as a conspicuous religious symbol. It was possibly an imitation of the northern minaret of the Great Mosque of Damascus, which was also located next to the mosque's courtyard, though the craftsmen at Cordoba would not have had firsthand experience of the Syrian building.[33] If it was a reference to Syrian architecture, then it was clearly intended to connect the Umayyads with their Syrian ancestors, a visual tool that past emirs had employed. It is also reasonable, however, to interpret the minaret in the tenth-century Islamic political context. The Umayyads were involved in a series of indirect military conflicts with the Fatimids over territories in North Africa; the contentious relationship between the two Islamic powers was exacerbated by the fact that they became rivaling caliphates and challenged the legitimacy of each other. Since the minaret was not a common practice in Fatimid mosques, its installation would physically proclaim the supremacy of the Umayyads over their enemies. In fact, after the Umayyads recaptured the city of Fez in Morocco from the Fatimids in 955, Abd al-Rahman III funded the construction of a higher minaret in the Qarawiyin Mosque in Fez.[34] By doing so, the Umayyad caliph openly subverted the Fatimid architectural traditions and installed a permanent mark of conquest.

In an ever-shifting political context, the building program under al-Hakam II became an expression of his political agenda that was unprecedented in previous expansions. Immediately after he ascended the throne in 962, al-Hakam II demolished the qibla wall and expanded the prayer hall by twelve bays to the south, continuing the tradition of double-tiered horseshoe arches. He accentuated the first

[31] Glaire D. Anderson and Jennifer Pruitt, "The Three Caliphates, a Comparative Approach," in *A Companion to Islamic Art and Architecture*, ed. Finbarr Barry Flood and Gülru Necipoğlu (Hoboken: John Wiley & Sons Inc., 2017), 223-224.
[32] Bloom, "Rival Caliphates in the West during the Tenth Century," 61-62.
[33] Bloom, "Rival Caliphates in the West during the Tenth Century," 62-63.
[34] Bloom, "Rival Caliphates in the West during the Tenth Century," 65.

three bays of the central nave by enclosing it with two screens of intersecting polylobed arches (Fig. 13) on the sides and covering it with a ribbed vault, which was later known as the *Capilla de Villaviciosa* (Fig. 14). The mihrab (Fig. 15) was built as a heptagonal chamber, crowned by a cupola in the shape of the mother-of-pearl shell. Around the mihrab was the maqsura (Fig. 16), the prayer space reserved for the caliph, which was divided into three bays, each of them separated by interlacing patterns of arches and topped by a ribbed dome (Fig. 17).[35] The central space, flanked by two bays, became part of the new transverse parallel to the mihrab, forming a T-shaped plan.[36]

The result of al-Hakam II's expansion was a luxurious display of the wealth of the Umayyad Caliphate as well as his royalty. The grandeur of the centrality of the plan was unprecedented in Andalusian architecture, but, at the same time, was not an original invention in the tenth century. The three longitudinal aisles in the center evoke the three apses in Christian churches, while the transverse in front of the mihrab marks a closer connection with the Christian cruciform plan (Fig. 18). These similarities, though, do not imply that al-Hakam II was consciously introducing a Christian presence into the mosque, for the axiality derived from Christian basilicas had long been favored by the Umayyads—in the Aljama Mosque at Madinat al-Zahra, for example.[37] What the caliph utilized was the ceremonialism generated by such a plan, which alluded to the dignified atmosphere of the Christian liturgy. The maqsura and the three domes, similarly, could be found in past Islamic architecture. The maqsura was commonly accepted as of Umayyad origins, first constructed at the Prophet's Mosque (Fig. 19) in Medina in 622, and later also present at the Great Mosque of Damascus. It was also probable that the Great Mosque of Damascus used to have the exact arrangement of three domes over the maqsura as at the Great Mosque of Cordoba, according to a source from the twelfth century, although only the Dome of the Eagle survives in the Damascus mosque today.[38] Nevertheless, the plan of al-Hakam II's expansion certainly perpetuated the architectural traditions of his Syrian ancestors. It culminated in a pronounced expression of the caliph's power, which was hardly imaginable in the early years of the Spanish Umayyads but was more than appropriate for a ruler who witnessed his caliphate rising to power to become part of the triumvirate of Islamic empires, in rivalry with Abbasid and Fatimid Caliphates.

The mosaic program in al-Hakam II's expansions was an equally innovative achievement, carrying as many political messages as artistic values. The central dome (Fig. 17) over the maqsura was covered with gold mosaics and decorated with green and blue glass tesserae, which formed intricate vegetal patterns—they were found not only on the surface of the scalloped cupola with an octagonal base but also on the squinches and arches below. The facades of the mihrab (Fig. 15) and the two flanking chambers—the Bab Bayt al-Mal and Sabat chambers—were also glazed with gold leaf tesserae. Apart from the vegetal and geometric shapes, there were also Quranic inscriptions (Fig. 20) in gold mosaics set off by red, yellow, or dark blue backgrounds.[39] Ibn 'Idhari, writing from the early fourteenth century, reported that

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[35] Bloom, "Rival Caliphates in the West during the Tenth Century," 69-70.

[36] Juan A. Souto, "The Great Mosque of Cordova: The Umayyad State of al-Andalus Made Architecture," *Hadeeth Ad-Dar* 31 (2010): 12.

[37] Dodds, "The Great Mosque of Córdoba," 21.

[38] Jonathan M. Bloom, "The Revival of Early Islamic Architecture by the Umayyads of Spain," in *The Medieval Mediterranean: Cross Cultural Contacts*, eds. Marilyn J. Chiat and Kathryn L. Reyerson (Clearwater: North Star Press of St. Cloud, 1988), 39-40.

[39] Marianne Barrucand and Achim Bednorz, "The Great Mosque of Cordova," in *Moorish Architecture in Andalusia* (Cologne: Taschen, 1992), 83-84.

> Al-Hakam had written to the king of the Christians on the subject of the mosaic incrustations and had ordered him to send capable worker, in imitation of that which the Umayyad caliph al-Walid had done at the time of the construction of the Great Mosque of Damascus.[40]

The "King of the Christians" referred to the Byzantine emperor Nikephoros II Phokas, who indeed dispatched a mosaicist along with a rich supply of gold tesserae to Cordoba. The style of the mosaic decorations at the Great Mosque of Cordoba is identical to the Byzantine ones, despite that the patterns, compared to the Byzantine figural representations, were much more simplified and that the tesserae were laid flat instead of at different angles to make use of the glistening effect of light reflections.[41] The Byzantine origin can also be attested by a recent study on the chemical composition of the tenth-century glass mosaics, which analyzed their high boron contents and associated them with other Byzantine mosaics made using raw materials from Asia Minor.[42]

It was unprecedented, however, for historic Andalusian monuments to be decorated with mosaics—part of the reason, of course, was the exorbitant cost of producing mosaics in Umayyad Spain. Despite this fact, it had been adopted by the Syrian Umayyads before, and this was clearly explained in the source from Ibn 'Idhari: it was a conscious emulation of the Great Mosque of Damascus and, as al-Hakam II wished to make this connection more explicit, was also from the Byzantines, who responded to the request of al-Walid more than two hundred years ago. Furthermore, the addition of the mosaics was a single act, for there was no evidence of other mosaic programs or the establishment of a mosaicist school after the construction. This contradicted Ibn 'Idhari's claim that al-Hakam II ordered apprentices to learn the craftsmanship of the Byzantine artisan.[43] In addition, the diplomatic exchange with the Byzantine Empire in the tenth century was not coincidental. The Byzantine Empire had been engaged in military conflicts with the Abbasid Caliphate in the Mediterranean since the early ninth century. After a series of victories in the mid-tenth century under emperors including Nikephoros II Phokas, the Byzantines held an advantageous position in the Aegean Sea. For the Caliphate of Cordoba, the presence of the Byzantine Empire in the east effectively restrained the military strength of the Abbasids, especially as the rivalry between Islamic polities intensified after Abd al-Rahman III declared himself a caliph.[44] As one of the greatest powers in tenth-century Europe, the Caliphate of Cordoba was able to confidently engage in a diplomatic dialogue with the Byzantine Empire and establish vital alliances to compete against its adversaries. The mosaic program, therefore, was not only the evocation of the mighty Umayyad Caliphate based in Damascus but also a strategic move on behalf of al-Hakam II with global politics in mind.

The political and religious intent of al-Hakam II was also implicitly communicated in the form of Quranic inscriptions, which, just like the mosaic

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[40] Ibn 'Idhari, *Bayān*, vol. 2, trans. Fagnan, 392, quoted in Dodds, "The Great Mosque of Córdoba," 22.

[41] Barrucand and Bednorz, "The Great Mosque of Cordova," 84.

[42] Gómez-Morón, María Auxiliadora, Teresa Palomar, Luis Cerqueira Alves, Pilar Ortiz, Márcia Vilarigues, and Nadine Schibille, "Christian-Muslim Contacts across the Mediterranean: Byzantine Glass Mosaics in the Great Umayyad Mosque of Córdoba (Spain)," *Journal of Archaeological Science* 129 (May 2021): 105370, https://doi.org/10.1016/j.jas.2021.105370.

[43] Bloom, "The Revival of Early Islamic Architecture by the Umayyads of Spain," 38.

[44] Anderson and Pruitt, "The Three Caliphates, a Comparative Approach," 245.

decorations, were newly introduced to the Great Mosque of Cordoba in the tenth century. The epigraphic program (Fig. 20) was found on the façade of the three bays of the qibla wall, as well as on the base of the central cupola over the maqsura. A calligraphic frieze under the vault recorded details regarding al-Hakam II's project—the commissioner, the supervisor, the craftsmen, and the date of completion—as was typical of other Islamic monuments.[45] The text inscribed on the rectangular frame on the façade of the mihrab offers a description of the construction, phrasing it religiously,

> Praise be to God, master of the worlds who favored al-Hakam II, the servant of God, the prince of the faithful … for this venerable construction and helped him in the building of this eternal place, intending to make this mosque more spacious for his subjects, something which both he and they greatly wanted.[46]

The inscription portrays the caliph as a pious ruler and justifies his opulent expansion, which was to satisfy the demands of the community and faithfully serve God. The actual reaction of his subjects, however, was contradictory to his claim. People heavily criticized the expanded mosque for its lavishness and, according to Abd al-Wahid al-Marrakeshi, at first they refused to pray in it.[47] This was why later historians including Ibn 'Idhari consciously attested that the project served a rightful cause, assuring their audience that the mosque was "executed with the help of existing funds as well as from pious foundations."[48]

The Quranic verses from the epigraphic program were carefully selected, both in the form of complete quotes and a combination of fragments, to convey messages centered on divine guidance, total submission, orthodox faith, and predestination. The inscription on the surface of the central dome, for example, reads,

> O you who believe, bow down and prostrate yourselves and adore your Lord, and do good, that you may prosper. And Strive in His cause as you ought to strive, He has chosen you and has imposed no difficulties on you in religion, it is the cult of your father Abraham; it is He who has named you Muslims, both before and in this, that the Apostle may be a witness for you.[49]

The quote demands religious submission from Islamic subjects, underscoring that life is predestined by the will of God and that only a divinely guided life may be blessed with happiness. There is also praise for God's omnipotence, stressing the orthodoxy of the Umayyad belief,

> God is He, other than whom there is no other god, who knows all things,

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[45] Barrucand and Bednorz, "The Great Mosque of Cordova," 84.

[46] Evariste Lévi-Provençal, *Inscriptions arabes d'Espagne* (Leiden: E. J. Brill, 1931), 15-16, quoted in Dodds, "The Great Mosque of Córdoba," 23.

[47] Dodds, "The Great Mosque of Córdoba," 23.

[48] Ibn 'Idhari, *Bayān*, vol. 2, trans. Fagnan, 390, quoted in Dodds, "The Great Mosque of Córdoba," 19.

[49] Manuel Ocaña Jiménez, "Las inscripciones árabes de la Mezquita de Córdoba de época contemporánea," *Corduba Archaeologica: Boletín del Museo Arqueológico Provincial de Córdoba*, no. 3, vol. 1 (1977): 153-161, quoted in Khoury, "The Meaning of the Great Mosque of Cordoba in the Tenth Century," 86.

both secret and open; He most Gracious, most Merciful.[50]

The defense for orthodoxy and the blatant condemnation of religious heresy is shown more conspicuously in the verse,

> Our Lord condemn us not if we forget that which You laid on those before us; our Lord lay not on us a burden greater than we have strength to bear, blot out our sins and grant us forgiveness, have mercy on us, You are our Protector, help us against those against faith.[51]

The invocation of universal religious messages through epigraphy instructed the Umayyad subjects about the exact doctrines that they should adhere to and strengthened the religious and political dominion of al-Hakam II. This formed a distant dialogue with the Dome of the Rock, the seventh-century Umayyad monument that was elaborately decorated with Quranic inscriptions, which acted as an assertion of faith and a refutation against Christianity. By ideologically constructing the Great Mosque of Cordoba as a venerable shrine in imitation of the Dome of the Rock, al-Hakam II urged for the purification and unification of his religious community.[52]

It is no coincidence that al-Hakam II favored the themes of predestination and orthodoxy, which are part of the doctrines of Sunni Islam, the sect of Islam that the Umayyads followed. The Quranic inscriptions were not only intended for his Umayyad subjects but addressed the ones who stood in opposition to the Umayyad faith. One such heterodox individual was the philosopher Ibn Massarra, who spread his teachings on free will in the community of his followers. His theory contradicted the belief of predestination in Sunni Islam and challenged the absolute authority of the caliph, which al-Hakam II perceived was a threat to his rule. The Abbasids and the Fatimids, who upheld the Shia doctrine, were another threat. The two caliphates were not only political opponents of the Caliphate of Cordoba but were also religious apostates, as al-Hakam II believed. It was necessary to firmly establish the Umayyad Sunni belief in the transcendence of God and the predestination of life, that is, matters that are among the greatest divides between Sunni and Shia. The Umayyads were also alarmed by a possible religious schism within the caliphate, which they feared the Shia Muslims were conspiring.[53] The unification of the Islamic community and the extermination of the heretics therefore became pivotal concerns for the caliphs of Cordoba. These formed the exact messages of al-Hakam II's expansion and epigraphic program.

Al-Mansur: Continuation of the Umayyad Legacy

Al-Hakam II was succeeded by his son Hisham II, and it was under his reign that minister al-Mansur became the de facto ruler of the Caliphate of Cordoba. In 987, al-Mansur began his addition to the Great Mosque after the city's population increased.[54] As it was impossible to expand the structure axially due to geographical

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[50] Jiménez, "Las inscripciones árabes de la Mezquita de Córdoba de época contemporánea," 153-161, quoted in Khoury, "The Meaning of the Great Mosque of Cordoba in the Tenth Century," 88.
[51] Jiménez, "Las inscripciones árabes de la Mezquita de Córdoba de época contemporánea," 153-161, quoted in Khoury, "The Meaning of the Great Mosque of Cordoba in the Tenth Century," 86.
[52] Khoury, "The Meaning of the Great Mosque of Cordoba in the Tenth Century," 86-88.
[53] Susana Calvo Capilla, "The Visual Construction of the Umayyad Caliphate in Al-Andalus through the Great Mosque of Cordoba," *Arts* 7, no. 3 (August 2018): 12, https://doi.org/10.3390/arts7030036.
[54] Bloom, "Rival Caliphates in the West during the Tenth Century," 77.

limitations, he widened the mosque to the northeast by eight aisles and extended the courtyard to the east (Fig. 21). The expansion, which increased the width of the mosque by almost fifty meters, surpassed the size of all past expansions and made the mosque the third largest in the Islamic world, only after two Abbasid mosques.[55] Though impressive as its scale may be, the program of al-Mansur was not so spectacular in terms of its ornamentation. He continued the tradition of horseshoe arches and alternating voussoirs in the extended prayer hall, emulating those of Abd al-Rahman I and II. He also reconstructed some of the intersecting arches from al-Hakam II's intricate program. However, he did not continue the symbols of royal privileges: the splendor of the qibla wall, the mihrab, and the transverse arcade. Al-Mansur's expansion almost entirely imitated the past, though it lacked the elaborate quality as seen before. The carvings on the column capitals became plainer, while the alternating red and white patterns of the horseshoe arches were not created by real voussoirs but painted stones, signifying an inferior reproduction.[56] Parts of the original northeast wall was also kept, delineating the boundary between the former hypostyle hall and al-Mansur's addition.[57]

By ordering a construction with an ambitious scale but less extravagance, al-Mansur consciously subordinated himself to the Umayyad rulers in the past. Perhaps al-Mansur was apprehensive that his administration would be recognized as illegitimate, as he did, in a way, usurp the power from Hisham II. He was thus prudent enough not to leave the most pronounced mark on the mosque.[58] Nonetheless, the respect for traditions is by itself a powerful political message. This is true when Abd al-Rahman I reflected on Syrian architecture and constructed the hypostyle hall; the architectural style at Cordoba was not entirely innovative, but it was precisely the elements of imitation that endowed the mosque with its powerful visuality. When al-Hakam II decided not to change the orientation of the qibla wall in his expansion, he similarly recognized the continuation of traditions as a display of legitimacy and ancestral honor.[59] For al-Mansur, subordination to the constructions of past rulers, who established the Caliphate of Cordoba as one the most formidable powers in the world, likely carried the same implication. The perpetuation of past legacies is one of the most prominent characteristics of the Great Mosque of Cordoba, making the Umayyad architecture a powerful political device in a complex historical environment.

The Mosque-Cathedral and an Everlasting Debate

The political messages that the Umayyads bestowed upon the Great Mosque of Cordoba were enduring, even when the Caliphate of Cordoba crumbled in the early eleventh century and when Christian armies took over the Iberian Peninsula in the Reconquista. In 1236, Cordoba was captured by Ferdinand III of Castile, and the mosque, subsequently, was reconsecrated as the Catedral de Santa Maria (Fig. 22).[60] Instead of demolishing the mosque, the Christians preserved it and appropriated its political meanings. This was not a customary practice during the Reconquista, however. Congregational mosques in Spanish cities were often replaced by

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[55] Bloom, "Rival Caliphates in the West during the Tenth Century," 78.
[56] Souto, "The Great Mosque of Cordova: The Umayyad State of al-Andalus Made Architecture," 13.
[57] Marianne Barrucand and Achim Bednorz, "The Great Mosque of Cordova," 85.
[58] Souto, "The Great Mosque of Cordova: The Umayyad State of al-Andalus Made Architecture," 13.
[59] Khoury, "The Meaning of the Great Mosque of Cordoba in the Tenth Century," 83.
[60] Dodds, "The Great Mosque of Córdoba," 24.

cathedrals, as in the cases of Lisbon, Huesca, and Valencia.[61] Even if the Christians did not immediately demolish some of the mosques, they usually altered the Islamic structures to serve Christian services and, when sufficient funds became available, ultimately erected new cathedrals on the original sites. The Great Mosque of Toledo, for instance, was reoriented to temporarily function as a cathedral after the Castilians seized the city of Toledo in 1085. It was then entirely replaced by a new Gothic cathedral in 1222.[62] The act of destruction announced the demise of the old Islamic order and the triumph of Christianity in territories that were, in the Christian sense, once lost. The Great Mosque of Cordoba, though, carried more profound implications. By preserving its grandeur and redefining its Islamic nature as Christian, the Castilian conquerors symbolically subjugated the Islamic past of Cordoba, converting the architecture into an everlasting victory monument. The reconsecration of the mosque was also accompanied by a sense of vengeance. In 997, al-Mansur ravaged Santiago de Compostela and removed the church bells to the mosque in Cordoba. Ironically, Ferdinand III heavily refuted this forceful religious hegemony of the Umayyads when he ordered the bells to be returned to their original shrine after capturing Cordoba.[63] The Great Mosque of Cordoba became a political setting for the clash between Islam and Christianity, which made it all the more meaningful.

The Christian attitude towards the mosque was complex. The appreciation for the Islamic architectural splendor was recorded in various Christian sources. While a number of chapels, altars, and naves were installed in the interior of the mosque in the thirteenth century, the Castilian kings also commissioned the restoration of the mosque, which was carried out by Mudejar[64] craftsmen.[65] The prudence of the Christians when modifying the architecture was manifest when Queen Isabella opposed Bishop Inigo Manrique's proposal of dismantling the central section of the mosque, resulting in the construction of a Gothic nave that was smaller than originally planned.[66] Similarly, in 1523, Bishop Alonso de Manrique's project of erecting a new cathedral within the mosque (Fig. 23) was objected to by the town council for devastating the mosque's magnificence. The project was implemented in the end, though Charles V, who personally approved it, purportedly regretted his decision.[67] The outcome was a towering processional nave and a massive dome that stood in the middle of the original prayer hall, an enigmatic amalgamation of two very distinct visual traditions.[68] Despite its controversy, the new Christian structure created an intense contrast between its imposing scale and that of the surrounding mosque, becoming a pronounced sign of religious dominion.

The Great Mosque of Cordoba, with the mixture of its Islamic and Christian identities after the Reconquista, continues to play a significant role in modern Spanish society. Today owned by the Catholic Church, the mosque is subject to the

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[61] Justin E.A. Kroesen, "From Mosques to Cathedrals: Converting Sacred Space During the Spanish Reconquest," *Mediaevistik* 21, no. 1 (January 2008): 136, https://doi.org/10.3726/83010_113.

[62] Kroesen, "From Mosques to Cathedrals: Converting Sacred Space During the Spanish Reconquest," 116.

[63] Dodds, "The Great Mosque of Córdoba," 18.

[64] The term "Mudejar" refers to the Muslims who remained in the Iberian Peninsula after the Reconquista.

[65] Ecker, "The Great Mosque of Córdoba in the Twelfth and Thirteenth Centuries," 118-122.

[66] Kroesen, "From Mosques to Cathedrals: Converting Sacred Space During the Spanish Reconquest," 122.

[67] Glaire D. Anderson, "The Cathedral in the Mosque and the Two Palaces: Additions to the Great Mosque of Cordoba and the Alhambra during the Reign of Charles V," *Thresholds* 25 (January 2002): 50, https://doi.org/10.1162/thld_a_00378.

[68] Dodds, "The Great Mosque of Córdoba," 24.

debate on modern Spain's cultural identity. After the fall of the Franco regime in 1975 and the weakening of the role of the Catholic church in Spain, the country began reasserting its identity and reexamining its cultural heritage. After the democratic transition in the 1970s, Spain began experiencing an influx of immigrants, which brought a series of demographic changes, among them is an increasing proportion of Spain's Muslim population.[69] These changes occurred with dissimilar reflections upon the country's role: the call for reviving Spain's Islamic past that was suppressed in the past decades, the demand for affirming the country's Christian identity, and the support for cultural pluralism and religious diversity. The controversy was precipitated when Spanish Muslims repeatedly demanded the right to prayer in the mosque in the 2010s, which was rejected by the Catholic Church. The Muslims' claim that the monument was initially a mosque was refuted by the proof of the existence of the Basilica of Saint Vincent. Archaeological findings from the 1920s and 1930s were presented and the exhibitions of the Museum of Saint Vincent were held in the mosque, asserting the Christian nature of the monument.[70] It was equally disputable when the Catholic Church revised the official name of the Great Mosque of Cordoba for multiple times and suppressed the Umayyad history of the mosque in the brochures distributed to tourists.[71] While the Umayyads constructed a political narrative on the origin of the mosque in the tenth century, the Catholic Church did the same when it presented historical accounts deliberately.

Conclusion

Ever since its construction on the site of a Christian basilica in 785, the Great Mosque of Cordoba has become endowed with rich political and religious meanings. In the contact between Islam and Christianity, the mosque was portrayed as a sign of religious dominance. In the rival politics between Islamic caliphates, it was used to assert the power of the Umayyad caliphs. Throughout centuries of expansions, the mosque also became synonymous with dynastic continuation, bearing witness to the Andalusian political and religious traditions and the legacy of Medieval Spanish history. When the Caliphate of Cordoba forever collapsed, the Great Mosque of Cordoba persisted. The messages of religious triumph and political hegemony were revived by the Castilian conquerors, though appropriated by the Christians for a different purpose. Amid the heated debate on the ownership of the Mosque-Cathedral in modern Spain, traces of the architecture's meaningful Medieval past are, again, present.

As D. Fairchild Ruggles notes, "The modern perspective on Spain's medieval history is an interpretation that emerges from our own political needs. *All* history is an interpretation—a reinterpretation—of the past. It is, after all, a tale told by a human narrator who cares about the storyline."[72] Whether it is the narrative constructed by Muslim historians celebrating the glories of al-Andalus, the tale of the Castilians retrieving their "lost land," or the modern controversy on the origin of the Mosque-Cathedral, the interpretation of the Great Mosque of Cordoba is always

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[69] Ruggles, "The Stratigraphy of Forgetting: The Great Mosque of Cordoba and Its Contested Legacy," 60-61.

[70] Ruggles, "The Stratigraphy of Forgetting: The Great Mosque of Cordoba and Its Contested Legacy," 57-59.

[71] Brian Rosa and Jaime Jover-Báez, "Contested Urban Heritage: Discourses of Meaning and Ownership of the Mosque-Cathedral of Córdoba, Spain." *Journal of Urban Cultural Studies* 4, no. 1-2 (July 2017): 139, https://doi.org/10.1386/jucs.4.1-2.127_1.

[72] Ruggles, "The Stratigraphy of Forgetting: The Great Mosque of Cordoba and Its Contested Legacy," 64.

driven by specific intents. It is only when one comprehends the complex messages of the Medieval past of the mosque, however, that one becomes capable of deciphering its meaning in the present. Despite the transformations that it has undergone, certain messages have become an eternal constituent of the mosque's identity.

Illustrations
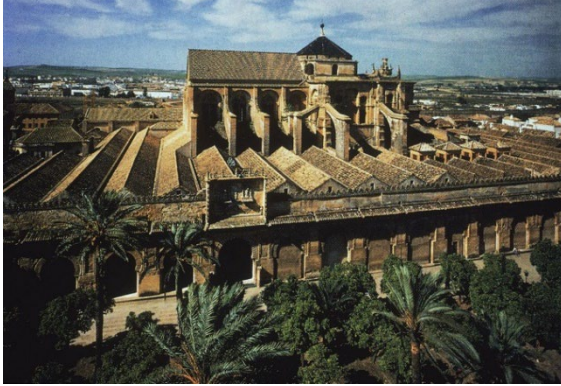
Figure 1. *Great Mosque of Cordoba exterior 785.*

Cordoba: Great Mosque: Ext.: aerial view. https://library-artstor-org.ezproxy.oberlin.edu/asset/ ARTSTOR_103_41822000006013.
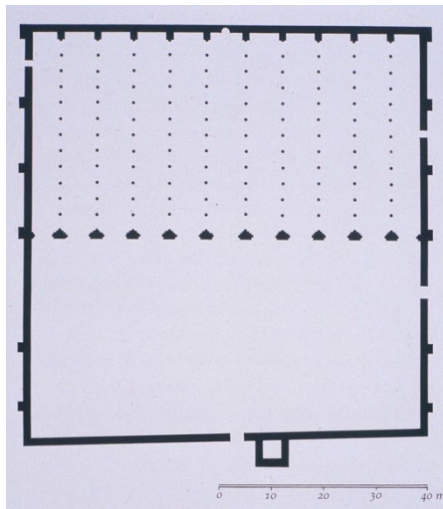
Figure 2. *Great Mosque of Cordoba plan, 785, begun 785.*

Cordoba: Great Mosque: plan.

https://library-artstor-org.ezproxy. oberlin.edu/asset/ARTSTOR_103_41822 003211396.
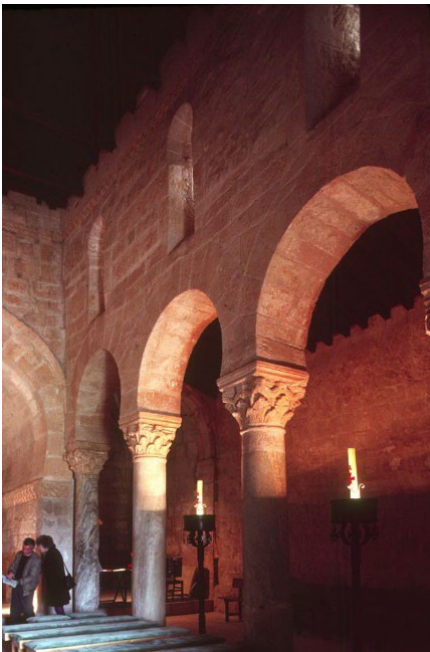
Figure 3.
*Basilica of Saint Vincent
excavations.*

*Paul, VanDerWerf, The
Floor Below, photograph,
Flickr, October 23, 2019,
https://flic.kr/p/2hzwpma.*
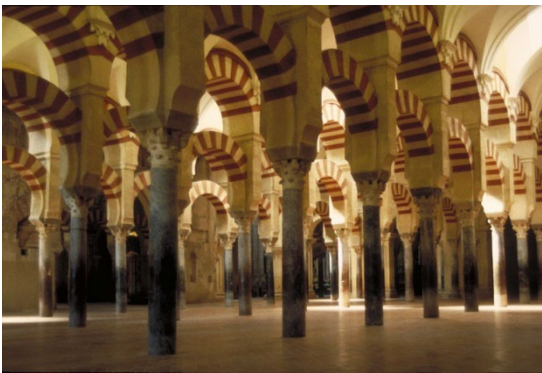
Figure 4. *Arcades of hypostyle hall
begun 785-786; enlarged to 987,
Image: 05/28/1996.*

*Great Mosque, interior, arcades of
hypostyle hall. mosques*

*https://library-artstor-org.ezproxy.
oberlin.edu/asset/
HSAHARA___1113_42457770.*

Figure 5. *San Juan Bautista de Baños de Cerrato
Anonymous, architect. Creation date: 651.*

*Church of San Juan Bautista.
https://library.artstor.org/asset/ASAHARAIG_11
1212446937.*

Figure 6. *Great Mosque of Damascus founded by Caliph al-Mu'awiya ibn Abu Sufyan; rebuilt by Caliph al-Walid ibn Abdul Malek; restored ahah. 709-15 on earlier foundations; restored and added to 1082-3; restored 1970.*

Umayyad Mosque. Architecture and City Planning, Architecture. https://library-artstor-org.ezproxy.oberlin.edu/asset/ ISLAMIC_DB_1039422284.

Figure 7. *Roman and Visigothic capitals begun 785.*
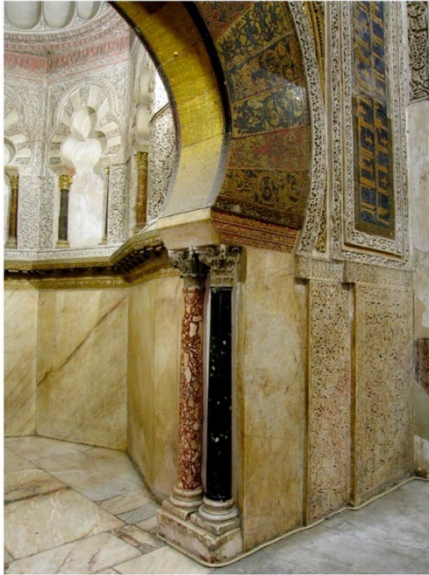
Cordoba: Great Mosque: Int. Roman Capital. https://library-artstor-org.ezproxy. oberlin.edu/asset/ARTSTOR_103_41822 000008522. 784-990,

Image: 2007. Great Mosque of Cordoba. Religious Buildings. https://library.artstor.org/asset/ASAHA RAIG_1113122160.

Figure 8. *Columns on mihrab. Capilla, Susana Calvo. Mihrab of the caliphal phase of the Great Mosque of Cordoba with the columns of ʿAbd al-Raḥmān II.*

In Susana Calvo Capilla, "The Visual Construction of the Umayyad Caliphate in Al-Andalus through the Great Mosque of Cordoba," Arts 7, no. 3 (August 2018): 5. https://doi.org/10.3390/arts7030036.
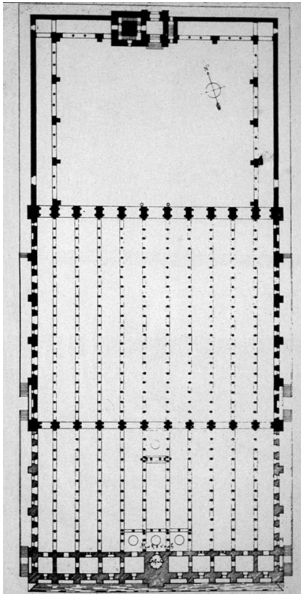

Figure 9. *Map of Umayyad, Fatimid, and Abbasid Caliphates in the tenth century. (The Institute of Ismaili Studies).*
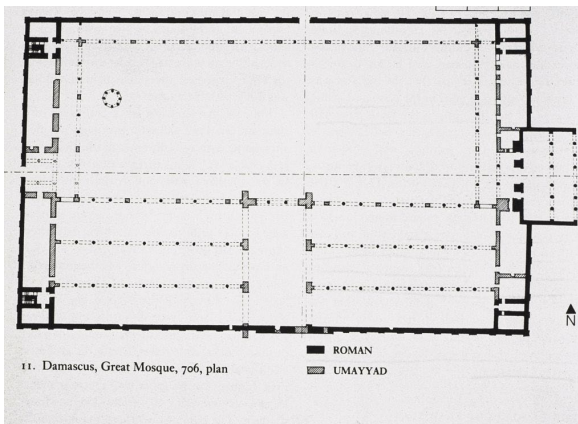

Figure 10. *Madinat al-Zahra 953-957.*

Madînat al-Zahrâ. Architecture.

https://library.artstor.org/ass et/HARTILL_12313014.

Figure 11. *Great Mosque of Cordoba plan, 965. Unknown. Great Mosque (Cathedral). Plan (after C. Nizet).*

Architecture. https://library-artstor-org.ezproxy.oberlin.edu/asset/ABRMAWR_ SITE_10312105608.

Figure 12. *Great Mosque of Damascus plan 706-15.*

https://library.artstor.org/asse t/ARTSTOR_103_41822003211 610.

Figure 13.
Polylobed arches
Architects: Unknown 8th, 9th, and 10th century architects; Hernán Ruiz the elder (Spanish, ca. 1475-1547); Hernán Ruiz the younger (Spanish, 1508-1569); Hernán Ruiz III (Spanish, ca. 1534-1606); unknown 17th and 18th century architects.

Mosque 784-786, with additions and modifications over time, Christian chapels from 13th century to 1766,

Image: 1969. Great Mosque of Córdoba. Architecture; Architectural Elements.

https://library-artstor org.ezproxy.oberlin.edu/asset/ MMA_KEIGHLY_10313360618.

Figure 14. *Capilla de Villaviciosa 961; 1523.*

Great Mosque From cathedral's west bay towards Capilla and Mihrab. Architecture. https://library.artstor.org/asset/HARTIL L_12312885.

Figure 15. *Mihrab 784-990*

Image: 2007. Great Mosque of Cordoba. Religious Buildings. https://library-artstor-org.ezproxy.oberlin.edu/asset/ASAHARAIG _1113122162.

Figure 16. *Maqsura founded by Caliph 'Abd al-Rahman I; additions and renovations made by Caliph 'Abd al-Rahman II, Caliph al-Hakam II, minister al-Mansur. 784-86; additions c. 833-52, 961-76, 987.*
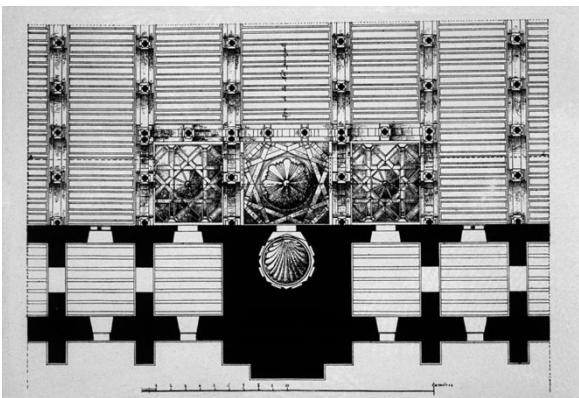
Great Mosque. Architecture and City Planning, Architecture. https://library-artstor-org.ezproxy.oberlin.edu/asset/ ISLAMIC_DB_1039585056.

Figure 17. *Dome in front of the mihrab 8th century. Mezquita Mosque and Cathedral; view of cupola interior. religious building.*

https://library-artstor-org. ezproxy.oberlin.edu/asset/LESSING_AR T_10313454930.

Figure 18. *Maqsura plan Unknown. 785-961.*

Great Mosque (Umayyad Mosque, Cathedral). Plan-Mihrab and maqsura. After C. Nizet..

Architecture. https://library.artstor.org/asset /ABRMAWR_SITE_1031210561 2.
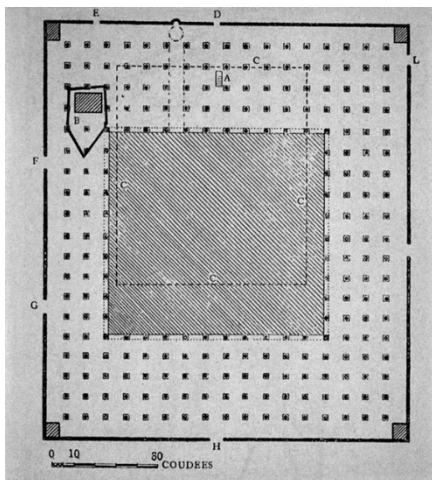
Figure 19. *Prophet's Mosque in Medina plan. Unknown. 707-709.*

Mosque of the Prophet. Plan. Medina. Architecture. https://library.artstor.org/asset/ABRMA WR_SITE_10312105613.

Figure 20. *Mihrab detail 784-990, Image: 2007.*

Great Mosque of Cordoba. Religious Buildings. https://library-artstor-org.ezproxy.oberlin.edu/asset/ASA HARAIG_1113122166.
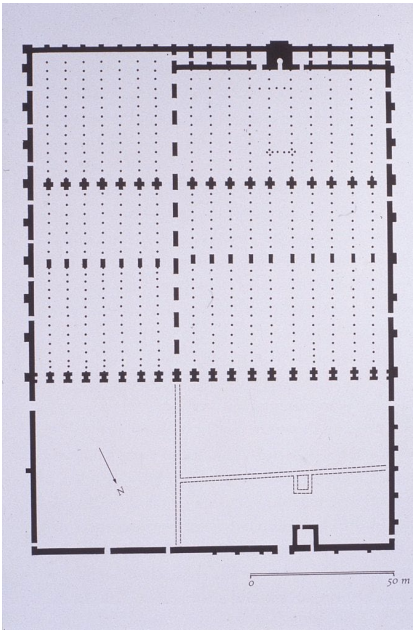
Figure 21. *Great Mosque of Cordoba plan, 987, begun 785.*

Cordoba: Great Mosque: plan as it appeared in 987. Mosque. https://library-artstor-org.ezproxy.oberlin.edu/asset/ARTSTOR_103_41822003211404.
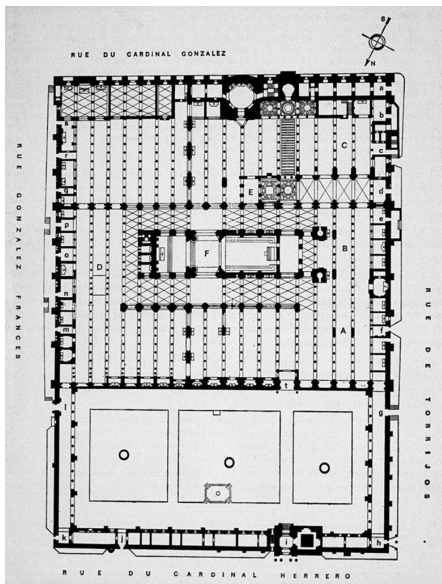
Figure 22. *Great Mosque (Cathedral) plan. Unknown.*
Great Mosque (Umayyad Mosque, Cathedral).

Ground plan- present state, 1979. (Plan by L. Golvin).
Architecture. https://library-artsto org.ezproxy.oberlin.edu/asset/ABRMAWR _SITE_10312105018.

Figure 23. *Charles V's cathedral*
founded by Caliph `Abd al-Rahman I; additions and renovations made by Calh al-Hakam II, minister al-Mansur. 784-86; additions c. 833-52, 961-76, 987; cathedral begun 1523, crossing added 1598. Great Mosque; Cathedral. Architecture and City Planning, Architecture.

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Why Do Girls Explore STEM Fields? Unfolding Reasons Behind Female Students' Decisions to Participate in or Quit STEM Careers

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Abstract

As the STEM field has rapidly developed, it has provided careers with great potential to the global community. This quickly growing field appeals to increasing numbers of women, encouraging them to explore and contribute to science. However, women currently remain underrepresented in STEM, particularly in occupations that require heavy math operations. This research provides a thoughtful literature review focused on factors impacting female students choosing to participate in or leave STEM careers. It presents the process of individuals forming self-efficacy and assessing STEM careers' utility value, both of which motivate women to study STEM. Nonetheless, stereotypes that explicitly deny women's math capabilities and implicitly segregate subjects according to different genders oppose women's participation in STEM careers. Meanwhile, the traditional distribution of family roles between men and women forces women to spend more time on family than their career development. Nevertheless, by providing female students with increasing opportunities to engage in STEM-related activities and encouraging women in STEM careers to balance family roles with work roles, we can eliminate the negative effects of stereotypes and build a diverse, inclusive STEM community.

Keywords: STEM careers, Female Students, Gender Gap.

1. Introduction

The field of Science, Technology, Engineering, and Mathematics, commonly known as STEM, plays an important educational role in shaping students' critical thinking abilities, advancing problem-solving skills, and enhancing job competitiveness. The economic values and psychological benefits of joining the STEM field motivate teenage Americans to major in STEM and ultimately become STEM workers. Although the total number of STEM majors increases annually, the field remains male-dominated, in which female students or workers are often underrepresented. In the broader STEM field, while women now account for 66% of bachelor's degrees

in social and behavioral science, they account for only 26% of bachelor's degrees in math and 24% of bachelor's degrees in engineering (Alexandria, 2023). This gender difference in STEM learning is not exclusively shaped by innate or immutable ability; it is influenced by social-cultural factors as well (Ceci et al., 2014). As women attempt to become STEM professionals, they have to balance expected family roles with their careers because of the intensive workload of STEM jobs. In addition to the expectation of women to raise families, the explicit and implicit biases within women's preferences, biology, and social experiences may encourage them to opt into (or out of) STEM careers (Diekman, 2010). These factors contribute to the social inequality of women engaging in STEM, leading them to sacrifice occupational pursuits and ultimately decreasing gender diversity in the United States STEM community.

Women's enrollment in the STEM field breathes new life into technological innovation and contributes to the nation's economic prosperity. In addition to intellectual and financial benefits, women's participation in STEM also benefits social development in the United States. Women in STEM provide innovative ideas that inspire young researchers' exploration of scientific issues. They also demonstrate female power in challenging gender stereotypes, redefining how femininity can coexist with being educated and competitive. Therefore, breaking the impression of male domination in STEM fields helps female students to prepare for choosing wider job options, achieving career ambitions, and balancing STEM identities with female identities.

2. Purpose Statement

This research cites sources dating back to the 1970s to show female scientists' contributions to STEM fields and their difficulties in continuing STEM careers. This research will also explore reasons for female students' participation in STEM careers by studying the following topics:
1. History of women's participation in STEM careers.
2. Psychological factors contributing to women's participation in STEM careers.
3. Social factors intervening in women's participation in STEM careers.

3. Definition of Terms

The term "femininity," describing the quality, state, or degree of being feminine or womanly, seems closely connected to female sexual identity (Merriam-Webster, 2023). However, characteristics related to the social perception of women do not appear naturally in an infant. According to Simone de Beauvoir, a French women's rights activist who states that "one is not born, but rather becomes, a woman," femininity is not a biological identity of newborn women, but rather an identity influenced by socio-cultural environments over time (Beauvoir, 1949). Influenced by de Beauvoir, French theories of femininity suggest that the patriarchal society relegates women to the negative pole of binary oppositions that justify masculine supremacy (Jones, 2020). In contrast to the masculine characteristic of competitiveness, women first need to be gentle, satisfying men's desires to possess them. In the year 2022, only 29% of members of the United States Parliament were women, indicating their lack of political control in the current patriarchal society (World Bank, 2022). They also must be mothers who provide care, nutrition, and love to their families. They are not allowed to sacrifice their family duties to pursue

their careers, or they will be denounced as "irresponsible" housewives. According to the World Bank (2023a), during the year 2003 to 2019, American women spent on average 16.81% (data ranging from 15% to 17%) of a 24-hour day on unpaid domestic work, while men only spent 9.88% (data ranging from 9%-10%) per day (World Bank, 2023b). The discrepancy of 1.66 hours per day suggests that women typically devote more time to caring for their families than men. Although this statistical time difference is not the sole driving factor for women leaving their jobs, performing femininity implies women devote more time to family roles than men, which forces women to abandon work.

The term "STEM identity" refers to a person's recognition of himself or herself as equal to a STEM scientist. Hence, people who have developed STEM identities can be described as "those who think about themselves as science learners and develop an identity as someone who knows, uses, and sometimes contributes to science" (Singer et al., 2020). These STEM scientists show a strong passion for exploring current issues, understanding the principles behind technological innovations, and promoting future scientific development. This strong passion enables people with STEM identities to view science as an integral part of their self-identity when describing themselves (Sáinz et al., 2020). They study STEM subjects not only due to financial benefits but also because of a long-lasting interest and high-level confidence in successfully attaining scientific knowledge.

4. Literature Review — Topic #1: History of Women's Participation in STEM Careers

Several studies reveal the distinct gender gap in STEM careers. For example, there are currently three times more men than women (75% vs. 25%) in the skilled technical workforce (Alexandria, 2023). Among 253 research papers that study STEM majors and employment from 2019 to 2023, 99.98% discuss gender, and 49.80% specifically study gender differences (López et al., 2023). Thus, it is important to narrow this gap and diversify future STEM communities.

4.1. History of Research Regarding the Gender Gap in STEM Fields

Since the Information Revolution in the mid-1980s, the number of occupations that require mathematical knowledge has increased dramatically. It is now evident that a lack of mathematical knowledge prohibits women from entering a variety of jobs. Without training in math, women cannot achieve true employment equality. When the female labor force gradually increased in the 1970s, most researchers realized this problem and studied women's lack of certain cognitive skills in order to explain how males excel in higher-level math classes. Many reviews conclude that while there might not be a sex-related difference in young children, male superiority is obvious by the time students reach junior high school (Fennema, 1979). These reviews fail to consider women's lack of access to opportunities to develop cognitive abilities compared to their male peers because the studies randomly select samples in secondary schools where the ratio of males and females enrolled in math classes is an average of 3.70 to 1 (Husén, 1967). However, in studies since 1974, when data is controlled for the amount of math studied, few significant differences in mathematics achievement between females and males are found (Fennema, 1979). More recent data of 7 million students in the United States show that the STEM test score of female and male students from grade 2 to grade 11 has a variance lower than 0.1, representing trivial intellectual differences (Hyde, et al. 2008). That is to say, on

most occasions, the impact of limited access to educational resources on a student's math achievement outweighs the impact of innate differences.

4.2. Women's Increasing Participation in the STEM Field

After the Women's Liberation Movement in the 1960s, the idea of gender equality spread throughout the United States, calling for women's rights to be educated and participate in the workforce. Generations of women inspired by this idea started STEM careers and challenged this male-dominated field. The number of women earning degrees rapidly increased over the years. By the year 2019, 65% of female STEM workers had a bachelor's degree or above. From 2011 to 2019, the percentage of women who obtained science and engineering degrees increased from 44% to 46% of all degree holders (Alexandria, 2023). However, despite women's active overall participation, they remain underrepresented in STEM fields that require intensive math operations, including math, computer science, and engineering. For example, in the traditionally male-dominated field of engineering, women's share of total bachelor's degrees was only 23% in 2019. Female scholars were also minorities in high-level post-secondary education, earning 25% of doctoral degrees in STEM subjects in the year 2019 (Charlesworth & Banaji, 2019; Alexandria, 2023). Hence, one can see the persisting gender gap in STEM careers, especially for jobs that require high-level mathematical operations.

5. Literature Review — Topic #2: Psychological Factors Contributing to Women's Participation in STEM Careers

To understand the reasons behind students' choices to enter STEM fields, this research will analyze two psychological factors: self-efficacy and utility value.

5.1. Self-efficacy

The term "self-efficacy," when discussing STEM identities, refers to students' belief in their capacities to execute actions necessary for becoming STEM professionals. Self-efficacy forms through the repetition of expected results after students complete a specific task. This repetition motivates students, making them confident about their capability to ultimately succeed even after facing adversity. Furthermore, students' evaluations of their self-efficacy can determine how much effort they will expend and how long they will persist if they encounter obstacles (Bandura, 1977). Because students put continuous efforts into absorbing STEM knowledge, they become able to demonstrate a strong ability in STEM subject performance, raising their confidence in fully unlocking their potential in future careers. Thus, a sense of self-efficacy is highly indicative of students' plans to enter a certain occupation (Eccles, 1994).

To fully understand the role of self-efficacy in students' willingness to initiate STEM careers, this research breaks down the psychological process of forming self-efficacy into two stages: developing the ability to master and developing the ability to compete. Figure 1 shows the progression from students experiencing cumulative successes to reaching the ability to master to achieving the ability to compete.

Figure 1. *Formation of Self-efficacy*

5.1.1. Stage of Forming Self-efficacy #1: Ability to Master

When students experience cumulative success in studying STEM, they meet their expectations of mastering knowledge. Studies indicate that accomplishing mastery goals, which refer to goals of gaining task mastery, significantly correlates with academic performance for all genders (Poortvliet, 2016; Shibley & Kling, 2001).

Firstly, academic successes, such as obtaining good grades, reflect students' capabilities of grasping math concepts, solving complex problems, and analyzing scientific topics. A good example of STEM students' academic success is a study of Binghamton University's undergraduates, showing that engineering students (with an average GPA of 3.14) often perform slightly better academically than average students (with an average GPA of 3.04) (Kokkelenberg & Sinha, 2010). Academic success not only gives students access to credentials for their careers but also fosters their confidence in contributing to scientific developments.

Secondly, students' skills in researching real-world problems, such as building math models for community amelioration, prove their capabilities to use professional knowledge to aid social welfare. This ability to apply science authentically is especially important for female scholars because they often aspire to improve the global community (Sáinz et al., 2020). Learning problem-solving skills for real-life situations informs women of STEM technology's ability to benefit local citizens, inspiring them to contribute to the study of public health, auxiliary technology, and so on (Singer et al., 2020).

Both academic success and the application values of STEM motivate students to set mastery goals, enabling them to attain a standard of competence defined by continuous self-improvement (Poortvliet, 2016). Setting mastery goals provides students with a standard measurement to check their progress in understanding new knowledge, especially when they are taking rigorous courses. As students gradually complete mastery goals, they will acquire sufficient knowledge to support their career development and have a strong sense of achievement (Bouffard et al., 1995).

5.1.2. Stage of Forming Self-efficacy #2: Ability to Compete

If students complete their mastery goals, their proficient STEM skills will allow them to enter the next stage of STEM careers: developing the ability to compete. Being competitive stimulates students' desires to gain expertise, harness creativity, and achieve success. In addition to motivating students to practice skills, competition drives students to accomplish mastery goals. By competing against their peers, they can learn from their rivals' experiences, find where they need to acquire knowledge, and ultimately achieve success in future careers. Research shows that the impact of competition on the pursuit of a STEM career is three times stronger when students attend multiple contests, which supports their positive influences on STEM students (Miller, et al., 2018).

5.1.3. Coexistence of Femininity and Developing Competence

Unlike the majority of male students, whose development of personal competence is always encouraged by socio-cultural values, some female students struggle to choose between preserving femininity and being competitive, since the latter option makes them "more masculine" in the perception of others. This question of whether it is appropriate for female students to be as competitive as their male peers is often regarded as the cause of a gender gap in STEM learning. In the 1970s, due to distinctively different social expectations for men and women (i.e. women as

housewives and men as workers), many believed not only that men and women differed but that possession of "masculine" characteristics precluded possession of "feminine" characteristics (Spence & Helmreich, 1978). Women who failed to practice femininity according to stereotypes defining women as subordinate (e.g., women entrepreneurs in STEM) lost the approval of their friends and families (Martin, 2003).

In recent times, however, influenced by Women's Rights and Gender Equality Movements, it has become more popular to recognize that any person has a mixture of multiple gender characteristics. Several studies demonstrating the success of females who expressed certain masculine characteristics have challenged the binary division of gender characteristics (West & Zimmerman, 1987, 2009). Thus, the ability to compete does not imply female students' rejection of femininity but rather demonstrates the hybridity of femininity and masculinity. Women who actively compete in STEM fields have stronger associations between self and STEM identities, holding fewer stereotypes about the limitations or expected image of a specific gender (Dunlap & Barth, 2019). In 2014, a study that held 49 in-depth interviews with women who work in so-called masculine jobs reported their advantages in work settings, including fewer assumptions about their incapabilities and more offers of additional training and knowledge, which enabled them to receive "similar treatments to men" (Dozier, 2018). Hence, the wide recognition of hybrid gender characteristics will improve both female workers' emotional health and their social adaptation ability.

5.2. Utility Value

The term "utility value," when discussing STEM career choice, refers to the values of learning STEM as integral to students' future careers. It suggests that STEM occupations ought to satisfy workers' physical and psychological needs. Figure 2 shows different forms of utility values and their effects on workers' vision of life experiences.
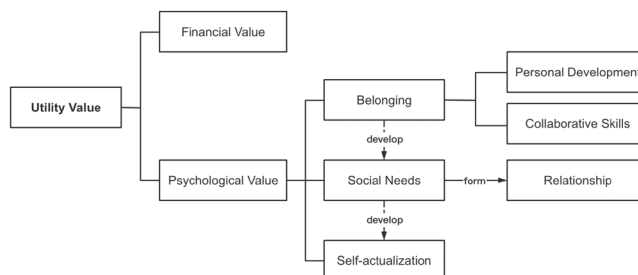
Figure 2. *Forms of Utility Value[1]*

5.2.1. Utility Value Category #1: Financial Value
An ideal job should satisfy workers' financial needs and support their daily expenses.

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[1] Figure 2 shows two dominant forms of utility value: financial value and psychological value. Psychological value can be further transformed into a process of STEM employees locating a sense of belonging (i.e., developing personal and collaborative skills), satisfying their social needs of stable relationships, and reaching the state of self-actualization.

Moreover, well-paid occupations enable workers to be economically independent, allowing them to have rich material lives and take care of family members. For STEM workers, a stable career with great growth potential usually provides sufficient income. In 2023, STEM workers had a median wage of $64,000, higher than the $40,000 earned by those working in non-STEM occupations. The same was true for women, who earned $60,000 in STEM occupations and $36,000 in non-STEM occupations on average (Alexandria, 2023). Consequently, most STEM occupations can fit workers' salary requirements, and this expanding field will continuously feed millions of families across the United States.

5.2.2. Utility Value Category #2: Psychological Value
In addition to economic values, psychological values also play a significant role in determining workers' understanding of certain occupations' utility values. Ideal jobs offer psychological values that support workers' personal growth and collaborative skills, such as locating belonging, attaining social needs, and accomplishing self-actualization.

5.2.2.1. Belonging
The term "belonging" refers to workers' feelings of comfort in their working environments. For STEM employees specifically, an inclusive workspace will offer a place for them to foster self-efficacy and establish competence in their workplaces. Moreover, workers can cultivate collaborative skills by meeting with like-minded colleagues and finding a community where they can thrive. For instance, many female workers are attracted to activities that involve cooperation with group members or classmates. These group-based research projects energize them to interact with other professionals and ignite their desire to share common interests in STEM fields with a larger audience (Maltese & Tai, 2011).

5.2.2.2. Social Needs
If careers offer social values to workers, they can establish long-lasting relationships with people who also have STEM identities. These relationships provide workers with opportunities to discuss professional techniques with other experts. Furthermore, because female scholars need external support to overcome negative experiences related to gender stereotypes, the quality of their career relationships is important to job satisfaction, especially when they represent minorities in male-dominated STEM fields. Therefore, the formation of intimate social bonds often contributes to women's persistence in pursuing a STEM career. Relatives, tutors, and parents who mentor women or engage them in technical tasks become their role models, making these connections deeply relevant to female students' lifelong passions for exploring scientific knowledge (Sáinz et al., 2020).

5.2.2.3. Self-actualization
The term "self-actualization," also known as the highest level in Maslow's hierarchy of needs, refers to the "full realization of one's creative, intellectual, and social potential through internal dive" (Maslow, 1943). In a STEM career, the job that pushes its workers to fully develop potential and fulfill their expectations of success will help them achieve self-actualization. For female scholars, STEM-related experiences would not only practically prepare them for rigorous mathematical tasks, but also allow them to become self-sufficient professionals who are capable of learning quickly and solving problems autonomously (Sáinz et al., 2020).

In addition to fueling female scholars' growing professional skills, achieving self-actualization also sparks their spirits of altruism. Many women aspire to help

build a better world by working with people from other places or with living creatures (Sáinz et al., 2020). Some multidisciplinary scientific topics, such as public health, disease research, and medicine, often appeal to female scholars, since the products of their work directly solve current issues and promote global equality. These areas merge the sympathetic characteristics of femininity into STEM research, helping female scholars to seek STEM identities in their careers. With strong moral codes and compassionate hearts, they are enthusiastic about adding human value to the exploration of STEM knowledge.

6. Literature Review — Topic #3: Social Factors Discouraging Women's Participation in STEM Careers

Although many female scholars participate in STEM occupations, social stereotypes and the pressure to raise a family may discourage them from continuing intensive research projects or putting most of their time into career improvement. In some cases, female workers may switch to lower-income jobs or even quit STEM careers. In others, even though some female workers perform as well as their male coworkers, the impression of women's incapability in STEM forces them to reject femininity to prove their competence, causing psychological struggle (Van & van der Molen, 2016). Figure 3 shows how stereotype threats and family obligations may result in women quitting certain occupations.
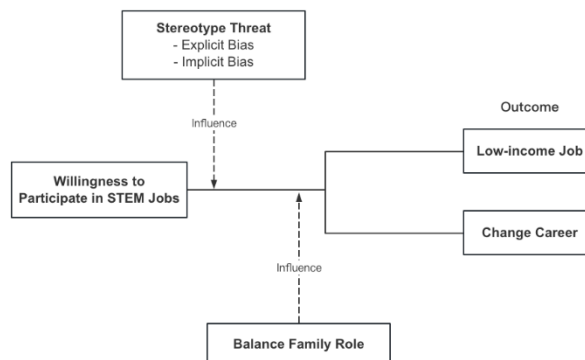
Figure 3. *Impact of Stereotype Threat and Family Role on Causing Women to Quit STEM*

6.1. Stereotype Threat

Negative stereotypes trigger several disruptive psychological processes that threaten female students' performances in STEM subjects. The idea that women are not capable of learning math lowers female students' expectations of their math abilities as early as the start of their education, and the assumption of male superiority can be strongest during their post-secondary education experience (Wang & Degol, 2013). These stereotypes can reduce women's confidence in STEM learning through either explicit expressions by other people or the implicit effects of subconscious activities.

6.1.1. Explicit Bias

The term "explicit bias" refers to stereotypes that are directly expressed to female learners, undermining their STEM learning ability. Because parents, teachers, and tutors believe that guiding students to meet social expectations of gender enhances students' social adaptability, they directly communicate their beliefs about gender to students, even guiding them to follow sex-typed behaviors (Eccles, 1994; Lytton & Romney, 1991). For example, elders believing in gender stereotypes may refuse to provide female students with certain opportunities to learn science, while offering boys more resources to develop cognitive skills (e.g., purchasing science kits, trips to museums, etc.), thus labeling STEM-related activities as male activities (Wang & Degol, 2013). As a consequence, women may perform poorly in high-level STEM classes after they grow up, making their so-called poor ability to master math even more difficult to improve. Ultimately, women scholars tend to form a fixed mindset and believe in an irreparable ability gap between male peers and themselves. In a survey of 1,364 students in secondary school that asked them to report whether they considered math, physics, and chemistry as male-dominated subjects, female students' ratings of these subjects' relation to male gender averaged 8 times higher than their male peers' ratings (Makarova et al., 2019). A fixed mindset could also cause anxiety in female students by informing them that they are representing a group expected to do poorly (Saucerman & Vasquez, 2014). This arbitrary conclusion then causes female students to underestimate the importance of their constant endeavors to improve their problem-solving skills, which further suppresses their willingness to enter STEM fields.

6.1.2. Implicit Bias

Unlike explicit bias, which denies women's math learning abilities directly, the term "implicit bias" refers to the gender segregation of subjects by suggesting which majors are more suitable for women's career development. This often occurs outside conscious awareness, exaggerating the importance of gender identities in influencing career preference (e.g., women are better at grasping literature concepts) (Nosek et al., 2002). For example, in a study that asked students from kindergarten through fifth grade to draw a scientist, there were only 28 pictures of a female scientist out of 4,807 pictures (Chambers, 1983). Students also tend to depict a typical math or physics teacher as a male teacher (Kessels & Taconis, 2012). Hence, part of the gender gap in STEM can be attributed to existing gender segregation in occupations, which influences how we define STEM jobs. Because women often avoid choosing math-heavy jobs, and the jobs they choose instead are usually less related to STEM, more women match themselves with non-STEM occupations (Jiang, 2021).

To address gender segregation, female students need to have access to math training materials to boost academic performance. When students take advantage of diverse educational resources, they are empowered to propose their unique methods of solving scientific issues and engage more in STEM learning (Gutiérrez, 2009). In addition, educators need to inform female students of underlying implicit biases. Through education on the science of implicit bias and its consequences on behaviors, students can become aware of gender stereotypes' negative influence on their school performance and intervene in its effects by refusing to accept them (Devine et al., 2012). For example, students can practice the techniques of "putting themselves in another's shoes" (perspective-taking), regarding group members as individuals rather than homogeneous group members (individuation), and generating role models who challenge stereotypical assumptions (counter-stereotype exposure) (Charlesworth & Banaji, 2019). As students gradually break implicit bias, they can

cultivate a more growth-oriented mindset in math learning, treating problem-solving ability as a skill that can be improved with practice rather than a skill determined by innate ability. Because the process of deep learning establishes lasting connections between neurons through recurring memories, encouraging female students to repetitively practice the application of math principles will give them a growth mindset, helping them to overcome academic failures and finally eliminating their acceptance of so-called math incapabilities due to gender (Boaler, 2015).

6.2. Balance Family Roles

Traditionally, women provide care, support, and nurturing to their families as mothers. They usually put more value on family-friendly jobs, and males put more value on intensive jobs that make a lot of money and possess high social status (Abele & Spurk, 2011). This is due to the concepts of male privilege inherent in traditional views of gender roles, which compel women to submit themselves to families while placing men in a dominant social position (Ferree, 1990). However, the professional knowledge of STEM fields frequently updates because of the rapid development of technologies and scientific issues. Research shows that STEM faculties who work more than 60 hours a week are more likely to publish, but married women report that they put significantly more time into household affairs than their male partners, forcing them to work for fewer hours (Jacobs & Winslow, 2004, Marks et al., 2009). According to the United States Bureau of Labor Statistics, in the year 2022, women generally spent an average 2.26 hours in household activities per day while men only spent 1.51 hours (U.S. Bureau of Labor Statistics, 2022). Since female STEM workers usually spend more time with families, they are less competitive in updating knowledge than the majority of their male coworkers. Thus, they may choose part-time jobs or switch to less stressful occupations.

As a result, the division of family roles and work roles between males and females results in inequalities. Research finds that when couples disagree about family responsibilities based on gender, both wives and husbands report higher levels of marital tension and conflict (Lye & Biblarz, 1993). The male-dominated family structure suppresses mothers' career development and leads to their lack of power in deciding family affairs. Meanwhile, fathers withdraw from raising children, doing chores, and holding family conversations, making their family role analytically invisible (Greenhaus & Beutell, 1985). This evidence indicates that it is necessary to give housewives employment rights in modern society. First, if women also participate in well-paid, competitive jobs, they can reduce the income pressure solely placed on a male family member. The research based on nationally representative samples shows that wives tend to share a more equal family power with husbands when they contribute more to the total family income (Zuo & Tang, 2000). Second, mothers in STEM also become role models, offering educational opportunities that spark interest in STEM subjects to their children and potentially affect their career choices. Third, mothers' employment increases marital satisfaction. If a husband shares family roles with his female partner, he will have a stronger bond with his wife and children. Both husbands and wives reported greater enjoyment of daily activities with their spouses if the husband is family-oriented than if he is not (Greenhaus & Beutell, 1985). Men who often connect with women in STEM fields, particularly in romantic relationships with female STEM workers, hold fewer stereotypes toward women who aim to become STEM scientists (Dunlap & Barth, 2019).

7. Findings

Through considering the outcomes of multiple studies, this research finds several factors that contribute to female students' STEM career choices: psychological factors that motivate them to start a career and social factors that discourage them from continuing intensive work. Moreover, by discovering the underlying reasons for women's low participation rate in STEM, further research can help women accept the mixture of multiple gender characteristics and balance STEM identities with femininity. Figure 4 shows how forming career interests and encountering career threats will influence women's choices of continuing or quitting their STEM careers.
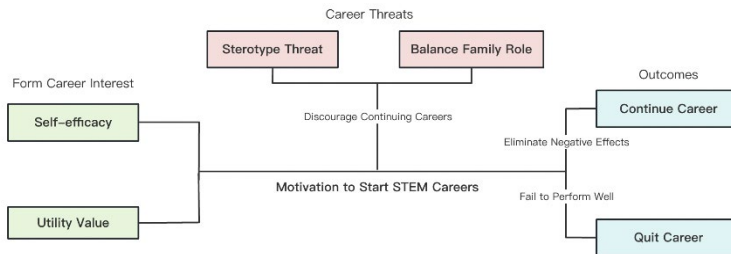

Figure 4. *The Model of Women's Career Path in STEM*

The formation of career interests contains two parts: students' feelings of self-efficacy and agreement of career utility value with personal expectations. To obtain self-efficacy, students need to experience cumulative success in academic settings, raising their confidence to accomplish mastery goals. This will further contribute to students' competency in STEM subjects, motivating them to put more effort into STEM research and persist when facing difficulties. Specifically, women in STEM's competencies demonstrate a hybrid of femininity and masculinity, which is beneficial when challenging male-dominated fields. In addition to self-efficacy, both financial value and psychological value will determine a job's utility value for female students. STEM careers usually have a higher average income than other occupations, so they meet most students' financial needs. From the psychological perspective, to encourage female students to join STEM careers, companies should offer places of belonging, satisfy their social needs of forming long-lasting relationships, and help them to fully unlock their potential (achieve self-actualization). Women in STEM also add human values to the field due to their ambitions of contributing to global welfare.

        However, stereotypes and demands of performing family roles often make women less motivated to continue STEM careers. Stereotypes can be either explicit or implicit. While explicit stereotypes directly cause women to underestimate their math potential, implicit stereotypes classify certain career fields as "more suitable for women than STEM." To eliminate the impact of stereotypes, educators should inform students of implicit bias' negative consequences and actively utilize habit-breaking methods to navigate students through developing a growth mindset. In addition to stereotype threats, many female workers quit intensive STEM careers due to the pressure of raising children and accompanying husbands. This family role division based solely on gender not only leads to husbands' absence from family activities but also suppresses wives' career development. Thus, allowing married women to continue their careers increases marital happiness since the pressure on the family budget can decrease, and parents can maintain a deeper relationship with their

children. This also eliminates the stereotypes held by male members because women in STEM demonstrate their power in equally competing against men.

To more comprehensively understand STEM women's employment situations, future researchers can focus on the effect of information technology on fostering female students' self-efficacy. Nowadays, search engines and AI models provide easy access for households to learn STEM knowledge online through free tutorials such as Khan Academy. This will reduce grades or teacher feedback's influences on female students' college major choices and career decisions. Also, in addition to stereotypes and family roles, other factors such as education level, income expectations, and working conditions impact STEM women's career developments, which are meaningful topics for further exploration.

8. Conclusion

This research shows the psychological factors that affect students' interest in STEM learning (self-efficacy and utility value). It also discloses social factors (stereotype threat and family role) that cause female STEM workers to switch to low-income occupations or give up STEM careers. This research reveals that the most direct and impactful reason for students to study STEM is their interest. Interests sparked by childhood experiences of understanding scientific issues, discovering scientific principles, and studying technological inventions will generate a current of motivation for students to further explore science. This encourages students to actively pursue knowledge when they are facing difficulties. In other words, even if female students encounter stereotypes that oppose their ability to grasp complex math concepts, their passion for STEM and excellence in academic performance will help them overcome difficulties in balancing femininity with STEM identities. By providing more educational opportunities for female students in STEM to continue their career development, more members from this underrepresented group can initiate a journey to explore science, making the global STEM community an inclusive, diverse, and actively developing place.

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Nanoparticle-Mediated Water Remediation: Investigating the Efficacy and Ecological Impact of Biosynthesized Zinc Oxide Nanoparticles for Removing Heavy Metal Ions From Contaminated Water

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Abstract

With the burgeoning crisis of global water pollution, heavy metals have demonstrated to play a key role in the proliferation of health risks associated with waterborne contamination for both humans and animals. However, current water treatments cannot effectively ease the problem of rising heavy metal contamination in water, which underscores the need to develop new and innovative technologies for water remediation. This study investigates the use of nanoparticles in water remediation and provides a comprehensive overview of the nanoparticle's mechanisms, synthesis, and characterization. Moreover, the study investigates the utilization of biosynthesized silica-based zinc oxide nanocomposites as a prospective remedial agent for absorbing heavy metal from contaminated water. The nanocomposites were synthesized using a sustainable method that involved the use of agricultural waste. The resulting nanocomposites had an average particle size of 30.52 nm and a pH at the zero-point charge 4.8. The optimization of the process has been achieved by adjusting the pH to 5.0 for nickel ions and 6.0 for copper and cadmium ions. Furthermore, it was also noted that the absorption efficiency of nano-SZO exhibits a positive correlation with the concentration. However, this association reaches a plateau point at a concentration of 0.4 g/L, suggesting the potential saturation of absorption sites. Distinct equilibrium times were also noted for each metal. Furthermore, an inverse relationship was identified between the increase in metal concentrations and the absorptive capability of nano-SZO. Alongside identifying the potential of nanoparticles in heavy metal remediation, the study also provides a comprehensive insight into the nanoparticle's limitations, such as its potential toxicity to organisms. By examining both the potential of this technology and its limitations, the study underscores the need for further research in the application of nanoparticles before extensive application in the field of heavy metal remediation

1. Introduction

1.1. Background and Significance

Water is an essential resource that all living organisms, including humans, need for survival of life on Earth. However, in recent decades, with increased industrial development and agricultural growth, heavy metal contamination has become a serious concern as dangerous substances and elements have been discharged into the air, water, and soil.

Heavy metals are elements with a density of around 4-5g/cm³ that are toxic to humans and living organisms even at low concentrations (Mathur et al., 2022, p. 1). Although some of the heavy metals are required in certain quantities to serve as micronutrients, high concentrations of these metals in the food chain could render harmful and adverse environmental effects, endangering aquatic ecosystems and the people who depend on them (Shanbehzadeh et al., 2014, p. 1). The increased intensity and geographical extent of heavy metal contamination in water can be attributed to three main factors: 1) the increased population and consequent demand for resources that have driven uncontrolled extraction and processing of metalloids from natural geological sources. 2) agricultural practices that necessitate heavy use of fertilizers, insecticides, and soil/plant additives that contain metalloid impurities; 3) natural occurrences like volcanic eruptions, earthquakes, and floods that release hazardous components into the environment and thereby poisoning nearby water bodies (Singh et al., 2022).

The increasing contamination of global water resources due to metal and metalloid proliferation is a prominent environmental and public health issue. Heavy metals, including arsenic (As), copper (Cu), nickel (Ni), cadmium (Cd), mercury (Hg), chromium (Cr), and lead (Pb) have become ubiquitous pollutants in the water, causing ecological disruptions and posing significant health hazards to living organisms.

Specifically, the pervasive presence of heavy metals in water systems has posed significant health threats to human populations. Chronic exposure to arsenic, a heavy metal found in many water systems, can cause a number of serious health concerns, including skin lesions and cancer. Likewise, lead accumulates in the body, and can eventually cause serious cardiovascular and neurological problems. Mercury, which is frequently dumped into waterways by industrial operations and absorbed by aquatic ecosystems, can harm kidneys and cause proteinuria. Chromium, a known carcinogen, increases the chance of motor neuron abnormalities and brain cancers when it is present in water, whereas cadmium can be harmful to reproductive health and cause lung, kidney, and bone disorders. Additionally, chronic nickel exposure can cause diseases like lung cancer, skin allergies, and cardiovascular issues (Mathur et al., 2022, p. 2).

Heavy Metal	Human Health Impacts	Common Sources
Arsenic	Skin damage, circulatory system issues, protein coagulation, nerve inflammation, muscle weakness, carcinogenicity	Naturally occurring, electronic production, agricultural applications, nonferrous smelters, metallurgy, coal-fired and geothermal electrical generation, tanning, pigments, antifouling paints, light filters, fireworks, veterinary medicine
Cadmium	Kidney damage, carcinogenicity, DNA damage, gastrointestinal irritation, hyperactivity, renal failure	Naturally occurring, various chemical industries, agricultural applications (phosphatic fertilizers), pigments, anticorrosive metal coatings, plastic stabilizers, alloys, coal combustion
Chromium	Allergic dermatitis, diarrhoea, nausea, vomiting, headache, neurotoxicity, kidney and liver damage	Naturally occurring, steel manufacturing metallurgy, refractory, chemical industries, plating, pigments, textile and leather tanning, passivation of corrosion of cooling circuits, wood treatment
Copper	Gastrointestinal issues, liver and kidney damage, anorexia, Wilson's disease	Household plumbing systems, naturally occurring, chemical and pharmaceutical equipment, pigments, alloys
Lead	Kidney damage, reduced neural development, carcinogenicity, high blood pressure	Lead-based products (batteries), household plumbing systems, antiknock agents, pigments, glassware, ceramics, plastic, alloys, sheets, cable sheathings, solder
Mercury	Kidney damage, nervous system damage, carcinogenicity, gingivitis, stomatitis, gastrointestinal issues, abortions	Fossil fuel combustion, electronic industries, fluorescent light bulbs, electrical and measuring apparatus, catalysts, pharmaceuticals, dental fillings, scientific instruments, rectifiers, oscillators, solders
Nickel	Allergic dermatitis, nausea, chronic asthma, coughing, carcinogenicity, hair loss	Paper products, fertilizer plating, electroplating, batteries, arc welding, rods, pigments for paints and ceramics, surgical and dental prostheses, moulds for ceramic and glass containers, computer components, catalysts
Zinc	Depression, lethargy, neurological signs, increased thirst, hyperactivity, physical dysfunction	Mining, coal, waste combustion, steel processing, agricultural applications (phosphatic fertilizers), anticorrosion coating, batteries, cans, PVC stabilizers, medicines and chemicals, rubber industry, paints, soldering and welding fluxes

Figure 1 - *Heavy Metal Health impacts and common sources (Heavy Metal, n.d., p. 3).*

The negative consequences of heavy metal contamination on human health and the environment underscore the imperative for effective, cutting-edge water cleanup techniques. Currently, contaminated drinking water and water used for irrigation in agriculture are the primary vectors for entering these toxic substances into biological systems and larger ecosystems. As metal(loid) resources are finite resources, effective remediation must achieve two parallel goals: detoxifying polluted water, and potentially extracting and recycling these elements from contaminated media (Mathur et al., n.d., p. 2). This dual approach strategy reduces immediate hazards to the public's health and encourages sustainable resource management. Therefore, to secure a sustainable and natural environmental landscape, it is imperative to investigate innovative remediation techniques, such as the nanoparticle-mediate methodologies investigated in this academic inquiry.

In recent years, nanoparticle-mediated water remediation has gained traction in scientific research as an innovative response to problems regarding water contamination. The efficacy of nanoparticles in water purification procedures stems from the unique properties of their small size, which typically falls between 1 and 100 nanometers (What Are Nanoparticles?, n.d.). Because of nanoparticles' small

size, they have a substantial surface area relative to their volume, thereby increasing their reactivity and absorption capacity for contaminants. This increased reactivity facilitates the conversion of toxic pollutants into less harmful molecules, giving nanoparticles access to a broader range of chemical interactions. Their nanoscale dimensions also permit reaching places that larger agents might find difficult to reach, resulting in more thorough pollutant clearance (Roy et al., 2021, p. 1). Nanoparticles appeal from an economic and environmental standpoint because of their potential prospects for resource recycling and prudent material utilization. By tailoring nanoparticles to selectively target particular contaminants, the accuracy of water treatment operations can be significantly increased. Therefore, adopting nanoparticle-based approaches may pave the way toward a new generation of water purification techniques that are more effective, long-lasting, and comprehensive.

This strategy leverages the unique properties of nanoparticles – their size, large surface-to-volume ratio, and reactivity – to enhance the efficiency, cost-effectiveness, and selectivity of pollutant removal from contaminated water. However, there is a need for a deeper, more nuanced analysis of its efficacy and a comprehensive assessment of the potential environmental implications associated with the widespread implementation of this approach.

This study aims to address this gap in the study of water-remediation by thoroughly investigating nanoparticle-mediated water remediation strategies. Specifically, the paper will focus on biosynthesized silica-based zinc oxide nanoparticles to absorb and remove heavy metal contaminants in the water. By evaluating nanoparticles' effectiveness in mitigating water pollution, exploring the various factors that affect their efficacy, and examining the potential environmental impact of their application, the research hopes to provide a more thorough understanding of this sustainable remediation strategy.

1.2. Overview of Current Methods for Heavy Metal Removal

Historically, many conventional treatment procedures have been applied for water remediation, each having specific applications and constraints. For example, many developing pollutants, like pharmaceuticals and personal care products (PCPPs) and endocrine-disrupting chemicals (EDCs), are difficult to remove or degrade by conventional methods, prompting a need for an alternative. In contrast, nanoparticles' reusability has the potential to reduce waste generation, improve treatment efficiency, and decrease energy consumption in comparison to conventional treatment systems. This section will examine the various traditional methods regarding their applications and limitations.

1.2.1 Physical Methods

1.2.1.1 Filtration
Several filtration techniques, including sand and membrane filtration (microfiltration, ultrafiltration, and reverse osmosis [RO]), are employed in water remediation and have demonstrated effectiveness. The filtration mechanism works by trapping pollutants inside the filter medium's pores; hence, the removal effectiveness is mostly size-dependent. Consequently, emerging pollutants such as heavy metal ions and other solutes could be challenging to remove when using conventional filtration processes. However, membrane-based approaches such as ultrafiltration and RO are comparatively more effective (Vince et al., 2008, p. 4). The limitation of the filtration technique is the requirement of external pressure for fluid movement across membranes, which can be energy-consuming. Moreover, to

prevent the common challenge of fouling, specific parameters must be maintained during membrane filtration for optimal performance. Regular backwashing is essential to prevent clogs; sometimes, strong chemicals are needed to repair the membrane. Additionally, RO-treated water frequently requires pH adjustments and remineralization, increasing the overall costs (Adeleye et al., 2015, p. 643).

1.2.1.2 Absorption

Absorption strategies are successful in the removal of several contaminants, comprising both organic and inorganic substances. The absorption methodologies typically utilize carbon-based substances to effectively capture pollutants inside their porous frameworks. While the cost of procuring raw materials for activated carbon is generally low, creating high-quality activated carbon using non-renewable energy sources can harm the environment (Vince et al., 2008, p. 9). When dealing with activated carbon, it is necessary to regenerate the carbon material to remove the accumulated organic compounds (Mohan & Pittman Jr, 2007, p. 4). Meanwhile, the production cost of alternative absorption mediums can be relatively high, and a significant drawback is their limited capacity for regeneration, which might result in substantial expenses. Although cost-effective alternatives are available, they frequently sacrifice efficiency, leading to problems of pore blockage. The absorption process primarily involves sequestering the pollutants without undergoing any major alteration, which results in the potential formation of hazardous byproducts that would require disposal. When the absorbing agent is not recycled on-site, it is classified as hazardous waste, leading to additional disposal expenses.

Ion exchange is another commonly employed absorption method for removing heavy metal ions from solutions. The mechanism of this process involves substituting heavy metal ions with less toxic ions. The cost for ion exchange is contingent upon the particular resin selected. Moreover, the process of ion exchange is characterized by its reversibility. The resin utilized in the ion exchange can be regenerated through the removal of surplus undesirable ions; however, this results in a significant loss of highly concentrated metals and other ions in the solution.

1.2.2 Chemical Methods

1.2.2.1 Oxidation

Chemical oxidation is recognized as an efficient method for treating a diverse range of organic pollutants. However, it is less effective in treating inorganic pollutants, such as heavy metals and dissolved minerals. Although oxidation is considered an efficient technique for the removal of emerging pollutants from wastewater, because of the often low concentrations of these contaminants present in wastewater, the overall efficiency of oxidation is hence lower. Oxidizing agents commonly used comprise of chlorine, ozone, and hydrogen peroxide. Commonly employed techniques are: wet oxidation, a treatment using air or oxygen as the oxidizing agent; and electrochemical oxidation, a method that employs an electrical current to induce a redox reaction (Martínez-Huitle & Ferro, 2006).

The limitations of oxidation arise pertaining to their utilization, expenses, and ecological ramifications. Chlorine, which is often used as an oxidizing agent, is corrosive, extremely toxic even at lower concentrations, and generates toxic byproducts that require additional remedial measures. Likewise, ozone, another often employed oxidizing agent, also has multiple downsides, including high energy consumption and significant financial expenses to facilitate the process of producing ozone on-site. This phenomenon arises because of the notable toxicity of the substance and the generation of detrimental byproducts. Furthermore, the

assessment of concentrated hydrogen peroxide reveals high energy requirements throughout the production and transportation phases. Wet oxidation, as an alternative technique, necessitates the use of elevated temperatures and pressure to facilitate the process of oxidation, which leads to high financial demands(Adeleye et al., 2015, p. 642). Chemical oxidation, which revolves around the handling of highly reactive chemicals, gives rise to concerns regarding safety and the occurrence of sludges generated by some reactions. The energy expenditure associated with chemical oxidation ranges from 0.3–0.4 kWh/m3, which is energy-intensive (Vince et al., n.d., p. 11). Electrochemical oxidation also necessitates a substantial amount of energy, and there is a periodic necessity to replace electrodes due to corrosion, making it an inefficient removal method when removing high-concentration persistent pollutants in wastewater (Contreras et al., 2003).

1.2.2.2 Photocatalysis

The application of photolysis or photocatalytic degradation - such as UV photolysis and TiO_2 catalyzed photolysis, has shown promising results in the degradation of a wide range of halogenated organic compounds, certain non-halogenated organic compounds, specific pharmaceuticals and personal care products (PCPPs), and heavy metals under specific conditions (Adeleye et al., 2015, p. 642). The degradation of low concentrations of volatile organic compounds (VOCs) using the photolysis method can pose challenges, which necessitates the combination of other treatment techniques. Moreover, the effectiveness of photolysis is often hindered by the optical properties of the water undergoing treatment, as the penetration of UV light is a prerequisite for the process. The life cycle impact of the UV photolysis might be significant due to its substantial energy consumption, and it has been shown that UV lamps necessitate regular cleaning and replacement, which could result in increased labor expenses (Vince et al., 2008). Therefore, the long-term effectiveness of photocatalysis is frequently hindered by water chemistry factors, such as water hardness, as well as the presence of co-contaminants (Adeleye et al., 2015, p. 643).

1.2.3 Biological Methods

1.2.3.1 Biological treatment

Biological treatment has been a widely utilized technology in eliminating various organic compounds from wastewater. However, it has demonstrated limited efficacy in removing halogenated organics and some non-halogenated organics (Martínez-Huitle & Ferro, 2006). Additionally, the removal of endocrine-disrupting compounds (EDCs) and pharmaceuticals and personal care products (PCPPs) by this method is generally inefficient, which can primarily be attributed to the lower quantities of PPCPs and EDCs compared to other pollutants. Hence, the extent of degradation achieved is also confined.

The efficacy of wastewater treatment with biological methods is also highly contingent upon the activity and presence of microorganisms, meaning that various factors, including the composition of water, loading rate, medium type, temperature, and extent of aeration, have the potential to influence the effectiveness of the treatment process. Biologically, treatment is also subjected to seasonal variations, perturbations, the occurrence of excessive nutrients, and the presence of waterborne contaminants, all posing a constraint to its efficacy. In addition, fouling and filter clogging are also common challenges encountered in bioreactors and biofilters, which results in limited long-term efficiency (Adeleye et al., n.d., p. 643).

1.3 Nanotechnology in Remediation of Pollutants

In recent years, the use of nanoscale items designed for environmental remediation purposes has increased exponentially. Nanomaterials have been employed in the remediation of polluted soil and groundwater in diverse hazardous waste locations, including areas affected by chlorinated solvents or oil spills. Nanomaterials exhibit a high surface-area-to-volume ratio, which leads to enhanced biogeological and chemical reactivity compared to materials at much larger scales. Hence, this attribute of the nanomaterials makes them exceptionally suitable for executing endeavors like water remediation. Manufactured nanoparticles also possess physiochemical, surface, and optical-electronic properties that offer solutions to problems that were previously difficult to address through conventional approaches (Roy et al., 2021, p. 6). In the next few sections, the paper will delve into more detail regarding the usage of nanoparticles in water remediation.

## 2. Related Work

2.1 Nanoparticles as adsorbents

Absorption is a surface-limited process. During the absorption process, molecules from a gaseous, liquid, or dissolved solid adhere to the surface, which will result in the formation of a coating or a film of molecules on the surface. The quantification of the absorption performance is often determined by evaluating the equilibrium absorption capacity, which is usually assessed with the material balance of the absorption system.
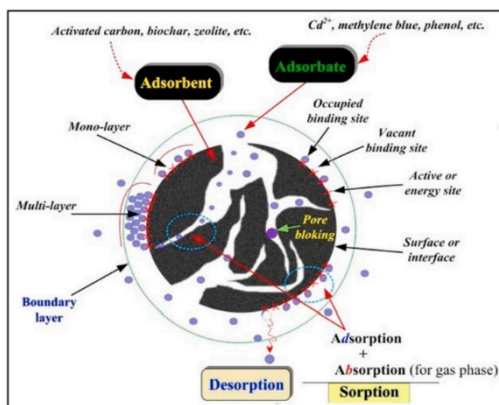
Figure 2 - *Absorption terms (Punia et al., 2021, p. 1531).*

Within all the different water treatment techniques employed, absorption is often regarded as the predominant method for eliminating pollutants from drinking water. The absorption technique is commonly applied because it demonstrates cost-effectiveness, simplicity in implementation, and the absence of secondary pollutants in the process of remediation. Nanoparticles possess properties and characteristics that render them effective absorbents, namely their substantial specific surface area and surface multi-functionality. The attributes of nanoparticles facilitate their chemical reactivity and formation of bonds with

neighboring molecules (Gómez-Pastora et al., 2014). Aside from commendable absorption capabilities, nanoparticles also possess additional advantageous attributes such as long-term stability. Nanoadsorbents can be broadly categorized into four groups: activated carbon, carbon nanotubes, nanoparticles, and polymeric nanoadsorbents, as shown in Figure 3.
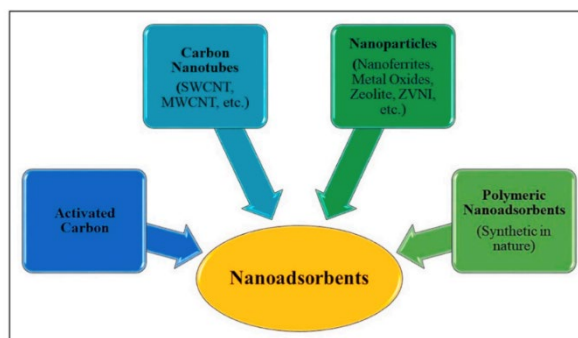

Figure 3 - *Categories of Nanoabsorbents (Punia et al., 2021, p. 1531).*

The nanoparticle absorption method involves the interaction between a porous solid medium and a multicomponent fluid or gas, which results in the creation of either physical or chemical bonds. This process provides flexibility in both design and operation, leading to great absorption efficiency (Al-Ghouti & Da'ana, 2020). Furthermore, the absorption mechanism is reversible, which allows absorbents to be regenerated by appropriate desorption methods.

The term "absorption" typically refers to a mass transfer process in which contaminants contained within a solution are transferred to a solid absorbent material. The absorption method is frequently utilized for the purification of water and wastewater, relying on the principles of pore filling, hydrogen bonding, hydrophobic contact, and ion exchange. The procedures include a diverse array of physical and chemical techniques that encompass a broad spectrum of absorption forces capable of effectively capturing specific contaminants ("Heavy Metal," n.d., p. 4). Physical absorption is a phenomenon that occurs as a consequence of the existence of weak Van der Waals forces of attraction. On the other hand, chemical absorption takes place when strong covalent connections are formed between the absorbent and the absorbate. The functionalization of iron oxide hydroxyl in an aqueous solution is a result of the interaction between water molecules and iron (Fe) atoms. The Lewis acid behavior of iron oxide is manifested by the formation of coordination bonds with molecules that possess lone-pair electrons on their surface atoms. The hydroxyl groups have amphoteric characteristics, enabling them to engage in interactions with both acidic and basic substances. The uptake of heavy metals from polluted water can be accomplished by utilizing the physicochemical properties of magnetic nanoparticles discussed earlier, along with the mechanisms of chemisorption and/or physisorption. The quantification of the absorption process can be achieved through the utilization of words such as absorption capacity and elimination efficiency. The presence of surface atoms leads to an increase in absorption capacity due to their heightened reactivity and instability, resulting in a greater number of unsaturated bonds ("Heavy Metal," n.d., p. 4).
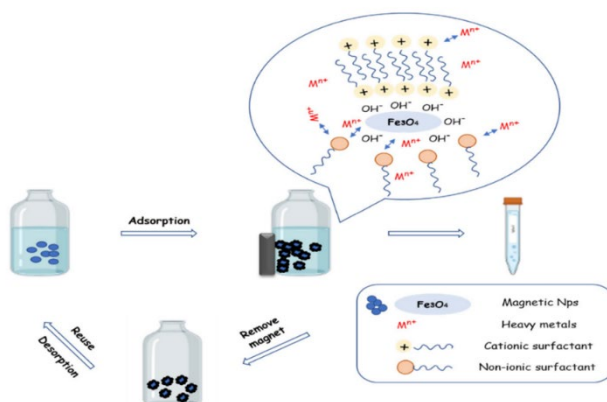
Figure 4 - *Water Purification Cycle (Heavy Metal, n.d., p. 5).*

2.2 Synthesis

The stages of the absorption approach encompass synthesis, characterization of magnetic nanoparticles, and subsequent evaluation of absorption. The stages work in correlation, where the outcomes of synthesis are then examined through the characterization processes. The synthesis of nanoparticles can be carried out using either top-down or bottom-up approaches, employing various chemical techniques, including coprecipitation, microemulsions, sol-gel synthesis, sonochemical reactions, hydrothermal reactions, hydrolysis, thermolysis of precursors, flow injection, electrospray synthesis, solvothermal method, and laser ablation (Heavy Metal, n.d., p. 6). Furthermore, variables like pH and temperature exert an influence on the dimensions and the robustness of nanoparticles. Various sizes and shapes of nanoparticles can be synthesized through the utilization of the aforementioned synthesis processes.

2.3 Characterisation

In order to investigate and analyze the properties of nanoparticle samples produced through synthesis procedures, a range of characterization methods can be utilized specific to each nanoparticle. The examination of the nanoparticle's physical, chemical, electric, magnetic, and optical characteristics can be facilitated through the utilization of characterization techniques. Through characterisation, it is possible to acquire information regarding several characteristics of the synthesized nanoparticles, including their dimensions, geometrical configuration, internal arrangement, surface topography, interatomic connections, elemental and mineral composition, surface area, signal strength, electrical and thermal conductivity, and compactness (Punia et a, 2021, p. 1537).

2.4 Zinc Nanoparticles

As aforementioned, this research focuses on the efficacy of zinc nanoparticles, which is a nanoparticle that is extensively employed in the field of water treatment. Zinc exhibits significant reductive properties, which facilitates the rapid breakdown of contaminants when employed in particle form. Zinx also exhibits a larger negative standard reduction potential, rendering it favorable for utilization as a reductant

(Bokare et al., 2013). Moreover, Nanoscale zero valent zinc particles (NZVZ) have been recognized as a highly effective reducing agent for the dechlorination of Polychlorinated dibenzo-p-dioxins (PCDD) due to their exceptional reactivity demonstrated through quick reaction rates (Punia et al., n.d., p. 1534). The utilization of alumina-supported NZVZ particles has also demonstrated efficacy in detecting the presence of arsenic and nitrate levels in drinking water, subsequently eliminating these contaminants through the process of absorption.

2.4.1 Zinc Oxide Nanoparticles

Zinc oxide (ZnO) has distinctive characteristics in terms of its optical properties, chemical sensing capabilities, semiconducting behavior, electric conductivity, and piezoelectric qualities (Fan & Lu, 2005). Zinc Oxide has a direct wide band gap of 3.3 electron volts (eV) in the near-UV spectrum. Additionally, it also possesses a considerable excitonic binding energy of 60 milli-electron volts (meV) at room temperature (Wang & Song, 2006) and an inherent n-type electrical conductivity. The aforementioned attributes facilitate the utilization of ZnO in a wide range of usage. For example, the large energy band gap of the Zinc oxide particles determines many of its properties, such as electrical conductivity and optical absorption. The emission of excitons has been observed to persist at elevated temperatures, and the conductivity of ZnO has been found to increase upon doping with various metals (Janotti & Van de Walle, 2009).

3. Experimental Design and Results

Zinc oxide Nanoparticles (ZnO NPs) have demonstrated considerable promise in the field of water treatment and cleanup due to their minimal toxicity, optical characteristics, bandgap, photocatalytic capabilities, and antibacterial activities. However, the investigation of green-synthesized silica-based zinc oxide composites as nanoadsorbents, using agricultural waste for valorization, remains unexplored. Hence, in this section, the report will review current explorations of the aforementioned nanocomposites and their efficacy in removing contaminants from wastewater. Specifically, the study reviewed presents the synthesis of silica-supported ZnO nanocomposites (nano-SZO) using rice husk, an agricultural byproduct with an abundance of silica and diverse phytochemicals. The nano-sized strontium zirconate (SZO) particles that were produced in the study reviewed were then investigated as a potential nano-adsorbent for the removal of heavy metal ions (nickel, cadmium, and copper) from synthetic wastewater (Garg et al., n.d., p. 2).

3.1 Methods

Nano SZO was fabricated through the following procedure. A quantity of 25 grams of powdered husk was boiled in the presence of a 2 M NaOH solution for a duration of 3 hours at a temperature of 353 Kelvin, resulting in the production of an extract. A solution with a concentration of 0.1 M of zinc nitrate hexahydrate was then subjected to treatment with the extract in a 1:1 ratio. This treatment was carried out with continuous stirring using a magnetic stirrer at a temperature of 353 K. The mixture underwent a 24-hour aging process, followed by centrifugation and rinsing with deionized water. Subsequently, it was dried in a hot air oven and kept for future utilization as nano-absorbents (Garg et al., n.d., p. 2).

The characterization of the surface morphology of nano-SZO was conducted by Scanning Electron Microscope (Model Jeol JSM-6100), while the associated

functionalities were analyzed using Fourier Transform Infrared Spectroscopy (Model Perkin Elmer Spectrum 400). The zeta potential of nano-SZO was measured using a Malvern zeta potential analyzer, specifically the Zetasizer Nano ZS90 model, throughout a pH range of 1 to 7. The characterization of the crystallinity of nano-SZO was performed using X-ray diffraction (XRD) using the PANalytical X'Pert Pro model. The pH of the solutions was measured using a microprocessor-based pH-meter, namely the Model 1010 Labtronics instrument. The concentration of residual ions was examined by employing an Atomic Absorption Spectrophotometer, namely the PerkinElmer PinAAcle 900T model.

Deionized water was used to create the synthetic media containing Cu2+, Ni2+, and Cd2+at a concentration of 10 mg/L; then, the solution was further diluted to achieve the necessary concentration. The experimental procedure involves conducting batch studies where a predetermined quantity of nano-SZO (ranging from 0.10 to 0.60 g/L) is added to a 100mL solution containing a known concentration of heavy metal ions (ranging from 10 to 20 mg/L). The mixture is then agitated at 298 K for a duration of 60 minutes. The pH of the solution was manipulated within the range of 1.0 to 7.0 by adding the appropriate quantities of dilute hydrochloric acid/sodium hydroxide, and the mixture was left to reach a state of equilibrium. A thermodynamic analysis was conducted within the temperature range of 288 - 328K. The sludge underwent a filtration process, and the concentration of remaining ions was measured. A solution of hydrochloric acid with a concentration of 0.1M was employed in the process of rejuvenating depleted nano-SZO particles obtained from the sludge (Garg et al., n.d., p. 2).
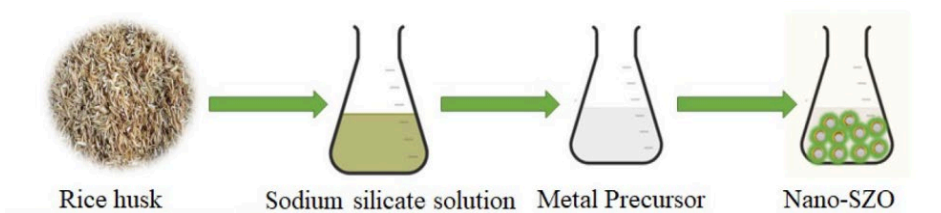
Figure 5 - *Fabrication Process of Nano-sized strontium zirconate (SZO) (Garg et al., n.d., p. 3)*

3.2 Results

Equilibrium adsorption capacity, qe, refers to the maximum amount of heavy metals that can be absorbed by the absorbent (nano-SZO) at equilibrium state. The efficacy of the nano-SZO, when present at a concentration of 0.1g/L, in the absorption of heavy metals at a concentration of 10 mg/L, is shown to be influenced by various factors:

3.2.1 pH level
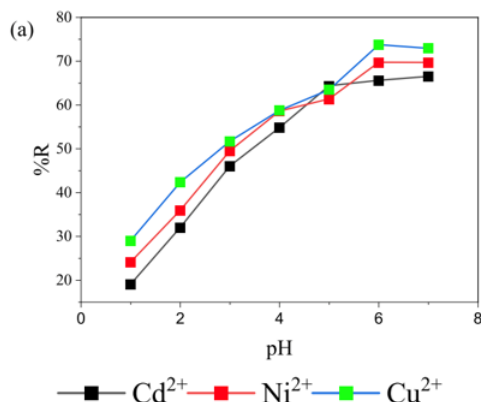
Figure 6 - *Variation of removal efficiency of nano-SZO with pH level (Garg et al., n.d., p. 5)*

As shown in Figure 6, There is a direct correlation between the pH level and the absorption capacity (qe), as an increase in pH results in an increase in absorption capacity. This optical pH level is demonstrated by the pH level when the graph reaches its maximum point; hence, based on the figure, the effect reaches its maximum point at pH 5.0 for Ni2+ and pH 6.0 for Cu2+ and Cd2+ions. The scientific reasoning behind optical pH level can be explained through chemical attraction. When the pH levels are lower than the point of zero charge (pHpzc) (a state where the surface of the nano-SZO has no net electric charge), the presence of an increased number of H+ ions results in the protonation of polyhydroxy and carboxy functionalities; this phenomenon exhibits repulsion with positively charged metal ions, which results in a decrease of absorption. On the other hand, when the pH level is above the point of zero charge (pHpzc), the absorbent's surface, which carries a negative charge, will subsequently exhibit enhanced affinity towards heavy metal ions as a result of electrostatic interactions (Fato et al., 2019 Gómez-Pastora).

3.2.2 Dosage of Nano-SZO

Another factor affecting the efficacy of absorbent removal is the concentration of Nano-SZO. Based on the data presented in Figure 7, it can be derived that there is a significant improvement in removal efficiency when the concentration of nano-SZO increased from 0.1 to 0.4 g/L. From 0.4 g/L, the graph plateaued, and increasing the dosage to 0.6 g/L did not yield any substantial increase in efficacy. This finding indicates that a concentration of 0.4 g/L is the optimal dosage for nano-SZO. The removal efficiencies at the optimal dosage for the respective metal ions are 91.52% for Ni2+, 93.89% for Cd2,+, and 96.91% for Cu2+. Initially, the augmentation of the dosage results in an amplification in the quantity of absorptive sites that are accessible for absorption. However, previous studies have observed that when nano-SZO particles reach more significant concentrations, there is a tendency for them to overlap, resulting in a decrease in overall efficacy (Khoso et al., 2021).
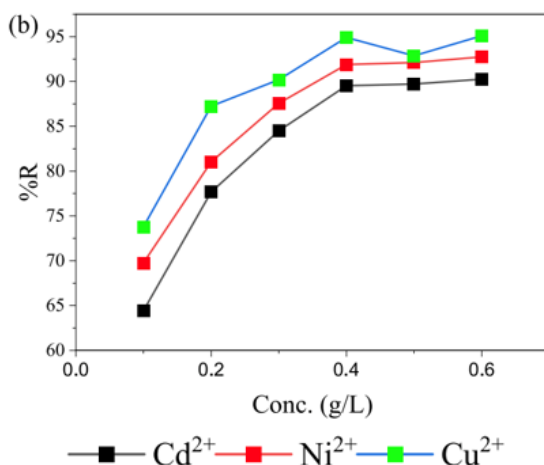
Figure 7 - *Variation of removal efficiency of nano-SZO with absorbent dosage (Garg et al., n.d., p. 5)*

3.2.3 Contact Duration

Throughout the experimental procedure conducted at the optical pH value, employing a nano-SZO dose of 0.4 g/L and maintaining a temperature of 298 K for 60 minutes, the heavy metal ions exhibited migration towards the surface of the nano-SZO material, subsequently penetrating its porous structure. The quantity of absorbed ions increases until it reaches a plateau after 20 minutes for Ni2+ and 15 minutes for Cu2+ and Cd2+. These variations highlight the distinct absorption behaviors among the metal ions, which can be attributed to their inherent properties and affinities towards the absorbent material. Nevertheless, a state of saturation, referred to as "equilibrium," was observed when the active sites inside the nano-SZO reached maximum occupancy, resulting in a decrease in the effectiveness of absorption (Jain et al., 2018).
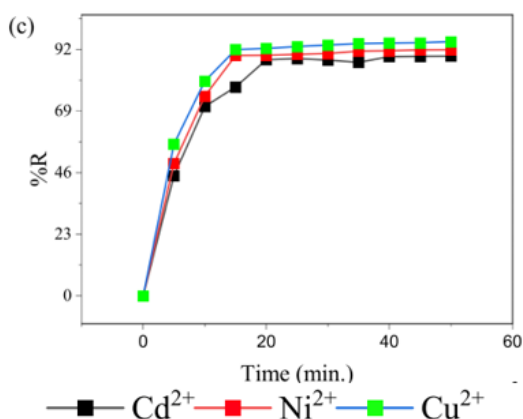
Figure 8 - *Variation of removal efficiency of nano-SZO with contact time period (Garg et al., n.d., p. 5)*

3.2.4 Initial Heavy Metal Ion Concentration
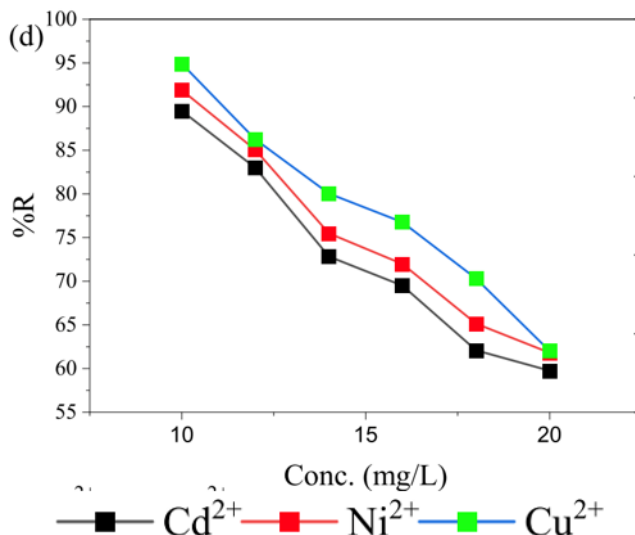
Figure 9 - *Variation of removal efficiency of nano-SZO with concentration of heavy metal ions (Garg et al., n.d., p. 5)*

The relationship between the efficiency of heavy metal ion absorption by nano-SZO and the initial concentration of these ions is inversely correlated (Fig. 9). Specifically, for low initial concentrations of heavy metal ions, the predominant absorption process takes place at high-energy sites on the nano-SZO; this can be attributed to the property of high-energy sites being more receptive to ion binding, which results in a higher overall absorption efficiency. Nevertheless, when the initial concentration of heavy metal ions is increased, the high-energy sites reach a state of saturation. As a result, the system depends on locations with lower energy levels for subsequent absorption. However, the lower energy sites exhibit diminished affinity towards ion binding, resulting in a decrease in the total absorption efficiency (Bansal et al., 2022).

4. Limitations of Nanoparticles as Absorbents

The optical characteristics and innovative applications of nanostructured ZnO have garnered significant attention in recent years. Furthermore, the broad exploration of pollution removal catalyzed by ZnO can be attributed to its distinct advantages, including its low cost, effective photocatalytic activity, and non-toxic nature (Chauhan et al., 2020). Despite the benefits, one significant limitation of the nanoparticle is its catalytic activity, which presently falls short of meeting the requirements for widespread commercial application. Furthermore, the nanosize of the particle has been observed to induce toxicity. (Recent and Emerging, n.d., p. 12). Hence, while nanoparticles offer promising advantages in the field of water remediation, they are not without limitations. The utilization of nanoparticles as adsorbents is a complex undertaking, characterized by various obstacles that have the potential to impact their effectiveness and broader implementation. This section

will explore the limitations associated with the use of nanoparticles in remediation procedures, providing insights into the many constraints and factors that need to be considered.

4.1 Harmful Effects on Organisms

Water remediation methods carried out by nanoparticles would distribute nanoparticles to aquatic ecosystems. Once present in the environment, these substances are potentially ingested and stored by species that inhabit the ecosystem. Within these organisms, the nanoparticles can either be eliminated by immunological responses or alternative mechanisms. Due to their distinctive physicochemical characteristics, nanoparticles function as exogenous entities within the organism, possibly interfering with its physiological process across different developmental stages, ranging from embryonic to adult phases (Exbrayat et al., n.d.).

During the embryonic stage, exposure to nanoparticles can result in the occurrence of abnormalities that may have fatal consequences. The small size of nanoparticles confers distinct characteristics that can interact with an organism's physical, chemical, and biological processes. Due to their tiny dimension, nanoparticles have the ability to traverse cell membranes, bypassing conventional defensive mechanisms. Subsequently, upon entry into the cellular environment, these entities possess the ability to navigate toward specific organelles, such as the mitochondria, modulating cellular processes and potentially triggering cellular death (Exbrayat et al., 2015).

In the event that the nanoparticles aren't small enough to pass through the cell membrane, they may nonetheless exert an influence on the cell by perturbing membrane processes, such as ion transportation or signal transduction. Additionally, attributes of nanoparticles such as their chemical composition or inherent positivity can also provide potential cytotoxic hazards; for example, the presence of positively charged nanoparticles has the potential to cause detrimental effects on the membrane lipid bilayers. Furthermore, surface coatings applied to nanoparticles have the potential to disrupt cellular structures (Hondroulis et al., 2014).

Moreover, the impacts of nanoparticles might be influenced by external factors, such as environmental pollution. The nanoparticles possess the ability to adsorb additional substances, hence intensifying their detrimental effects on organisms.

4.2 Harmful effects on humans

Human exposure to nanoparticles has been found to result in many harmful consequences, such as oxidative stress, lipid peroxidation, genotoxicity, lung illnesses, inflammation, and pulmonary pathological alterations (Patil et al., 2016, p. 16). The minuscule dimensions of nanoparticles provide them with the ability to be internalized by both cell mitochondria and the cell nucleus, hence potentially leading to cell mortality due to DNA mutations and significant structural impairment of mitochondria.
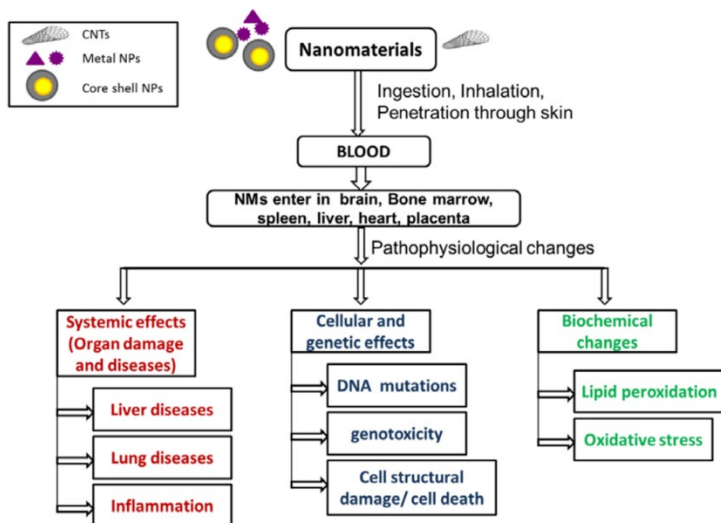
Figure 10 - *Human health implications associated with
exposure to nanoparticles (Patil et al., 2016).*

5. Conclusion

In conclusion, this study identifies the limitations of modern-day water treatment methods with the increasingly disastrous problems with water pollution and provides an examination of the nanoparticles-based water remediation through investigating the complex relationship between nano-SZO (nanoscale zero-valent iron) and heavy metals in aquatic environments. The study investigates how different factors affect the effectiveness of the nanoparticles' absorption of heavy metals. Crucial findings in our study include the significant impact of pH levels on the degree of absorption of the nanoparticles. It was observed that nickel exhibited the highest level of absorption at a pH of 5.0, while both copper and cadmium reached their maximum absorption levels at a pH of 6.0. Moreover, it was also observed that the absorption effectiveness of nano-SZO demonstrates a positive correlation with the concentration; however, this relationship reached a plateau at the concentration of 0.4 g/L, indicating the possibility of absorption site saturation. Different equilibrium times were also observed for each metal. Additionally, a negative correlation was observed between increasing metal concentrations and the absorption capacity of nano-SZO. The key findings of this study can be categorized into two aspects: firstly, nano-SZO exhibits considerable potential in the field of heavy metal absorption, however, it is also crucial to remain aware of the possible ecological and health consequences this technology may cause, which necessitates additional extensive investigations before implementing it extensively in water treatment paradigms.

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✵

Unveiling the Mechanism of Allicin: A Molecular Docking Study on its Interaction with SARS-CoV-2 Main Protease (Mpro)

Zhenpeng Liu

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Abstract

Allicin, a common organosulfur compound found in garlic, has enormous potential as a therapeutic approach to treat SARS-CoV-2, the causative agent of COVID-19. Building on existing evidence regarding the broad-spectrum therapeutic properties of allicin, we examine its interaction with the main protease (Mpro) of SARS-CoV-2, a key enzyme in the viral replication process. Utilizing the CDocker method, we conducted an in-depth molecular docking analysis to elucidate this interaction. Our findings suggest a robust interaction between allicin and the active site of Mpro, leading to potential disruption in Mpro's essential functional mechanisms—substrate binding and dimerization. This disruption could interfere with the protease activity of Mpro, thereby inhibiting SARS-CoV-2 replication. These observations underscore the potential of allicin as a putative inhibitor of Mpro and propose its consideration as a candidate therapeutic agent against SARS-CoV-2. This study adds to the collective scientific endeavor to develop effective and accessible therapeutics for the ongoing COVID-19 pandemic and fortifies preparedness for potential future coronavirus threats.

1. Introduction

1.1. Historical and Medicinal Significance of Garlic

Garlic (Allium sativum) has been a beloved spice and medicinal resource for thousands of years. Garlic was utilized by the ancient Egyptians as a remedy for diarrhea, with its therapeutic properties documented on papyrus dating back to 1500 BC and depicted on the walls of temples. Greek physicians Hippocrates and Galen also recognized its therapeutic properties and used it to treat a variety of intestinal and extra-intestinal diseases. In ancient Japan and China, garlic was used to alleviate headaches, flu, sore throat, and fever [1].

The use of garlic in traditional medicine remains prevalent, as it relies on the therapeutic properties of plants to address various ailments [2-4]. In the field of Traditional Chinese Medicine, garlic has been utilized for more than three millennia, owing to its bioactive compounds that have demonstrated positive effects on human health. Its medicinal properties are attributed to its diverse bioactive compounds, including organic sulfides, saponins, phenolic compounds, and polysaccharides, which have been extensively studied for their therapeutic effects [5].

1.2. Chemical Composition and Health Benefits of Garlic

Garlic is a complex plant that contains a wide range of chemical compounds with diverse properties. It has significant water content and is composed of carbohydrates, organosulfur compounds, proteins, amino acids, fiber, and essential vitamins and minerals [6]. The unique flavor, scent, and medicinal properties of garlic can be attributed to its organosulfur compounds, which can be classified as non-volatile and volatile.

In garlic, the stable antecedent compounds of sulfur encompass γ-glutamyl-S-allyl-L-cysteine and its corresponding sulfoxide, which is recognized as alliin (Figure 1) [6].
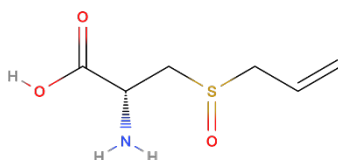
Figure 1. Chemical Structure of Alliin

Upon crushing or slicing garlic cloves, the alliinase enzyme that was originally contained within vacuoles is freed and interacts with the cytosolic alliin. As a result, a variety of thiosulfates are generated, the most significant being allicin (Figure 2 & Figure 3). Allicin is a volatile organosulfur compound that has been extensively studied for its antibacterial properties and health benefits [7]. The processing of garlic produces volatile organosulfur compounds (VOCs), which can be divided into three categories based on their chemical structures. The first category consists of thiosulfinates, which are formed enzymatically during the handling of raw garlic. The second group pertains to unstable organic sulfur compounds, specifically allicin (DAS), which is produced when garlic undergoes crushing or damage. Allicin is particularly unstable and breaks down into a variety of compounds, among which are diallyl sulfide (DAS), diallyl disulfide (DADS), diallyl trisulfide (DATS), and sulfur dioxide (SO_2). This group also includes methyl allyl disulfide (MADS) and methyl allyl trisulfide (MATS).

The final category includes water-soluble organosulfur compounds (WSOCs), which are produced during the extraction of garlic, as γ-glutamyl-S-allyl-L-cysteine (GSAC) decomposes into S-allyl-L-cysteine (SAC). Garlic-derived substances have been associated with beneficial effects on cardiovascular health, immune system disorders, and different forms of cancer due to their antioxidant, anti-inflammatory, and antimicrobial properties.
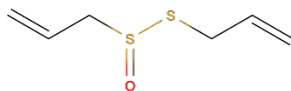
Figure 2. *Chemical Structure of Allicin*
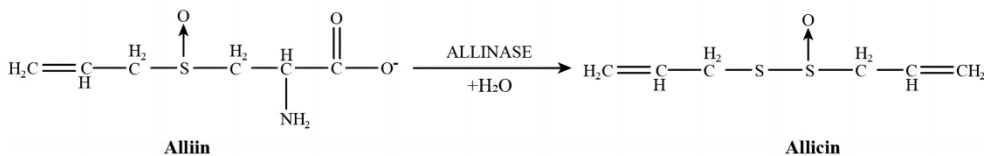
Figure 3. *How alliin turns into allicin*

1.3. Anti-inflammatory, Antibacterial, and Antioxidant Properties of Garlic Compounds

The health benefits of garlic are largely attributed to its organosulfur compounds. Garlic extracts have been shown to possess anti-inflammatory activity. Studies have indicated that the administration of alliin may reduce the expression of interleukin-6 (IL-6) and monocyte chemotactic protein (MCP-1) while increasing the expression of genes associated with immune response [8]. Furthermore, it has been discovered that the use of garlic extract can suppress the expression of IL-17 by peripheral blood mononuclear cells, while not impacting their IL-4 expression [9].

The oxidation of DNA, proteins, and lipids caused by reactive oxygen species (ROS) is a major contributor to the aging process and the onset of numerous diseases including cancer, neurodegenerative disorders, inflammation-related ailments, and cardiovascular conditions as well as age-related illnesses [10]. Garlic is laden with saponins, organosulfur compounds, flavonoids, and phenolic compounds, which together contribute to its antioxidant capacity. Water-soluble organosulfur compounds such as S-allyl cysteine (SAC) and S-allylmercapto-L-cysteine (SAMC), which are present in aged garlic extract (AGE), significantly contribute to this antioxidant potential [6]. The antioxidant effect of aqueous garlic extracts is enhanced through the synergistic interaction of these compounds with saponins, flavonoids, and specific nutrients.

These phytochemicals aid in the upregulation of antioxidant enzymes like superoxide dismutase (SOD) and catalase, and they enhance cellular glutathione (GSH) levels. This combined action serves to shield cells from the oxidative damage instigated by ROS [11, 12].

Extensive research has been conducted on the antibacterial properties of allicin and oil-soluble organosulfur compounds [13]. The stable organosulfur compounds found in garlic's aqueous and alcoholic extracts, including S-allylmercapto-L-cysteine, S-allyl cysteine, and S-methyl cysteine, have been shown to possess antibacterial properties. These nonvolatile compounds are present in both extracts. An extract from fresh garlic has been found to hinder the proliferation of a range of bacteria, including but not limited to Bacillus cereus, Staphylococcus

aureus, and Escherichia coli [14]. Sulfur-containing compounds within garlic can disrupt the formation of bacterial biofilms by inhibiting quorum sensing, which in turn interferes with bacterial adhesion as well as the secretion of extracellular polymers and virulence factors [15]. Furthermore, studies have demonstrated that the consumption of aged garlic extract (AGE) can bolster immune response by enhancing the activation and proliferation of certain immune cells, like natural killer (NK) and cytotoxic T cells in mice, as well as NK and T γ δ cells in humans [16-19]. Figure 4 provides a visual representation outlining the biological actions of allicin.
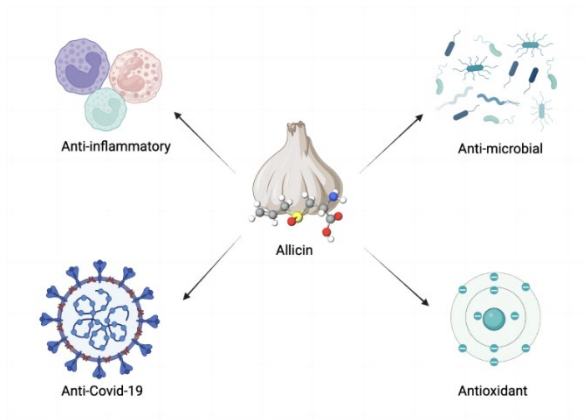
Figure 4. *Biological activities of allicin*

1.4 Introduction to SARS-CoV-2 and the Need for Novel Antiviral Strategies

While the therapeutic potential of garlic's organosulfur compounds in combating a range of diseases is well recognized, its capacity to influence viral infections is less understood and could be a key area of further exploration. Viral infections, particularly those caused by coronaviruses, have proven challenging to manage due to the viruses' ability to rapidly mutate and develop resistance against conventional antiviral therapies. In the face of the recent COVID-19 pandemic, the need for novel and effective antiviral strategies has become increasingly urgent. Given its broad spectrum of therapeutic properties, allicin could offer promising potential in this respect. This leads us to examine the possible role and efficacy of allicin in inhibiting the progression of SARS-CoV-2, the virus responsible for COVID-19.

SARS-CoV-2, or Severe Acute Respiratory Syndrome Coronavirus 2, is the pathogen that sparked the outbreak of COVID-19, an infectious respiratory disease that first surfaced in Wuhan, China, in December 2019 [20]. This recently discovered member of the coronavirus family is in the company of those responsible for severe acute respiratory syndrome (SARS) and Middle East Respiratory Syndrome (MERS). The virus, characterized as spherical and with diameters spanning 50 to 200 nanometers, is made up of four principal structural proteins: S (spike), E (envelope), M (membrane), and N (nucleocapsid). The S protein is especially key, as it governs the virus's ability to attach and fuse with host cells, thus commandeering the host cell's resources for its replication and spread within the body [21]. The arrival of the COVID-19 pandemic has triggered a global health crisis of unprecedented scale, with profound implications for public health, the economy, and societal life [22].

COVID-19 symptoms range from mild to severe, with the triad of fever, cough, and shortness of breath being the most reported. Furthermore, individuals have experienced additional indications such as weariness, muscular discomfort, head pain, diminished ability to perceive taste or smell, throat irritation, and congestion or discharge from the nose. Some individuals infected with SARS-CoV-2 may exhibit no symptoms, while others may experience a severe illness that requires hospitalization [23].

The disease's severity has been linked to dysfunctional immune responses, including decreased levels of T lymphocytes and white blood cells essential for combating viral infections [24]. Additionally, a hyper inflammatory state, referred to as cytokine storm syndrome, may occur. This syndrome involves an overproduction of pro-inflammatory cytokines, including interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF-α), and interleukin-1 beta (IL-1β), resulting in systemic tissue damage and potential organ failure [24-26].

The key to developing effective treatments and vaccines for COVID-19 lies in understanding its immunopathology. Numerous potential therapeutic strategies are currently under investigation, including antiviral drugs, immunomodulatory agents, and convalescent plasma therapy. In addition, several vaccine candidates have shown promising results in early-phase clinical trials.

One promising therapeutic target is the SARS-CoV-2 main protease (Mpro), also known as 3chymotrypsin-like cysteine protease (CCP or 3CLpro) [27]. The protein is a complex dimeric structure, composed of two identical subunits meticulously bonded together to form dual active sites. Its protein fold bears a striking resemblance to serine proteases such as trypsin, although it takes a slightly different approach to biochemical reactions. In this case, it is a cysteine amino acid and an adjacent histidine that shoulder the responsibility for the protein-cleaving function. This unique configuration is further complemented by an additional domain, which functions to fortify and stabilize the entire dimeric structure. Intriguingly, a significant feature of this structure is the presence of a peptide-like inhibitor lodged within the active site. This structure plays an absolutely pivotal role in modulating the proteolytic activity of the protein. The structure of SARS-CoV-2 main protease is highlighted in Figure 5 [28].
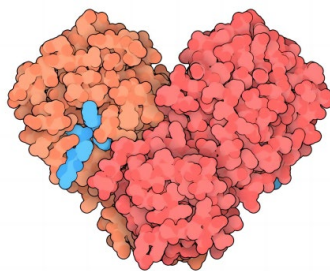
Figure 5. *Structure of SARS-CoV-2 main protease*

This non-structural protein plays a vital role in the processing of polyproteins into functional units necessary for viral replication and assembly in its dimer form. The highly conserved nature of Mpro among various coronaviruses makes it a compelling target for developing broad-spectrum anti-coronaviral therapeutics against COVID-19 [27, 29]. Drugs designed to target Mpro have the potential to hinder

viral replication and proliferation, exhibit wide-ranging antiviral effects, and diminish the possibility of drug resistance driven by mutation [26, 30].

1.5 Allicin as a Potential Therapeutic Agent for COVID-19

Emerging research has shed light on the antiviral mechanisms of allicin, a compound found in garlic, particularly regarding its interaction with the SARS-CoV-2 main protease, Mpro. Allicin is thought to interact with the catalytic active site of Mpro, composed of His41 and Cys145 residues [31, 32]. In silico docking analyses indicate that allicin can induce S-thioallylations at Cys85, Cys145, and Cys156 of Mpro, and at Cys622 of RdRp, suggesting a possible mechanism by which allicin might inhibit SARS-CoV-2 replication [33].

Additional in silico analyses with other garlic constituents, such as alliin and ajoene, demonstrate strong binding stability between the ligand and protein, along with multiple interactions at the Mpro active site. Furthermore, it has been observed that 17 garlic-derived organosulfur compounds, which account for 99.4% of the substances present in garlic oil, interact with the ACE2 receptor and Mpro in computational models, with substances like diallyl di- and trisulfides showcasing encouraging docking scores [34, 35].

These insights underline the potential of garlic's organosulfur compounds to serve as inhibitors of viral proteins and point towards the necessity of further exploring these compounds as potential therapeutic agents against COVID-19. However, there is a critical unanswered question: the precise mechanism by which allicin inhibits SARS-CoV-2, given the significant role of Mpro in the viral replication process, remains unclear. In this research, we aim to address this gap by proposing a hypothetical framework that links allicin and Mpro, exploring how their interaction might influence the progression of COVID-19. By doing so, we hope to contribute to the ongoing global efforts to identify effective therapeutics for COVID-19.

2. Materials and Methods

Analysis of the interactions between receptors and ligands during docking

The receptor's active site was ascertained through the evaluation of the ligand present within the main protease's crystal structure complex, sourced from the Protein Data Bank (PDB) with the identifier PDBID: 6Y84 [20]. Allicin's atomic coordinates were acquired from a 3D PUBCHEM download and subsequently underwent geometry optimization to determine the configuration with the lowest energy state. Utilizing the CDocker package integrated within Biovia's Discovery Studio 2020, these docking studies were carried out [36].

The Biovia Discovery Studio, provided by Dassault Systems, utilized the CHARMm molecular simulation software to enable a comprehensive exploration of various biological components. Its capacity ranged from calculating single point energies or minimizing receptor-ligand complexes using hybrid Quantum Mechanics/Molecular Mechanics (QM/MM) simulations through Dmol3/CHARMm.

In this analysis, in conjunction with docking, the standard dynamics cascade protocol embedded in Discovery Studio was leveraged to optimize atomic coordinates and appraise the selected poses. CDocker, a widely used molecular docking methodology, utilized CHARMm and operates within a grid-based framework. In the process, the receptor maintained its rigidity, while the ligands were permitted

conformational alterations during the refinement phase.

Random ligand conformations were created via high-temperature molecular dynamics and random rotations. These were then subjected to additional refinement through simulated annealing, followed by a final minimization step. For each configuration of the ligand, calculations were performed to determine both the CHARMm energy (consisting of the energy of interaction and ligand strain) and the exclusive interaction energy. The most favorable binding poses with the highest negative score were then selected and retained. Simultaneously, the atomic coordinates were optimized, and selected poses are evaluated using the standard dynamic cascade protocol within Discovery Studio.

3. Results

The molecular docking analysis of allicin with Main protease was conducted using the CDocker method. Figure 6 shows the energy-minimized molecular structure of allicin. The resulting docking interactions were visualized and analyzed in Figure 7. Figure 8 shows the 3-D allicin ligand interactions on docking at the active site of the SARS-CoV-2 main protease. The strong hydrogen bonds between allicin and the Glu166 and Asn142 amino acids are shown. These bonds are thought to stabilize allicin at the active site.
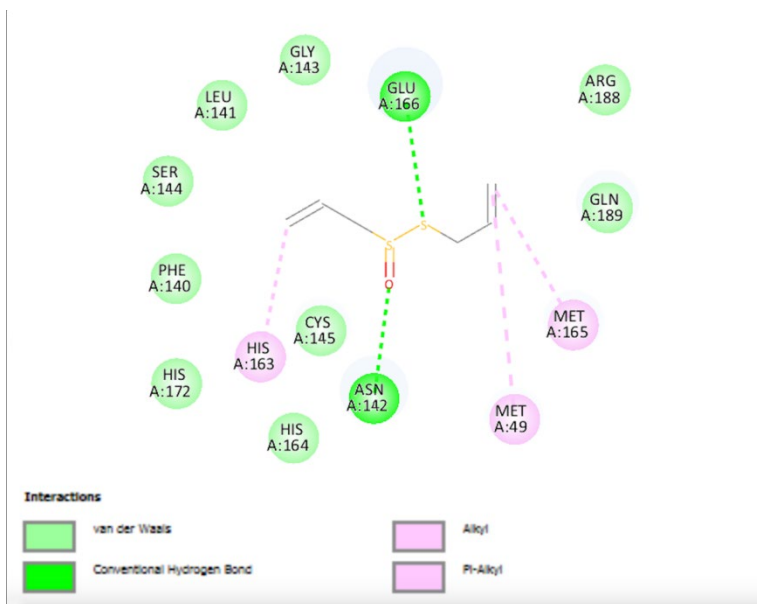
Figure 6. *The 2-D allicin ligand interaction diagrams for docking into the active site of the SARS-CoV-2 main protease*
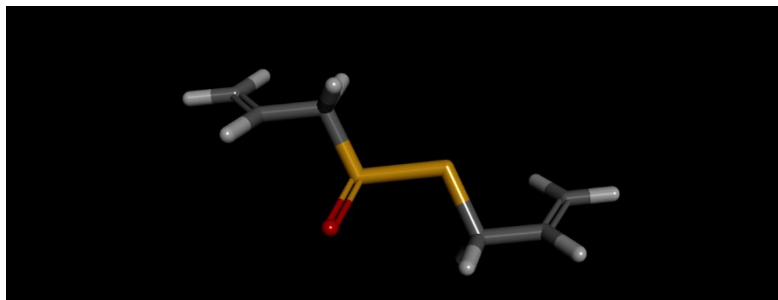
Figure 7. *The energy-minimized molecular structure for allicin*
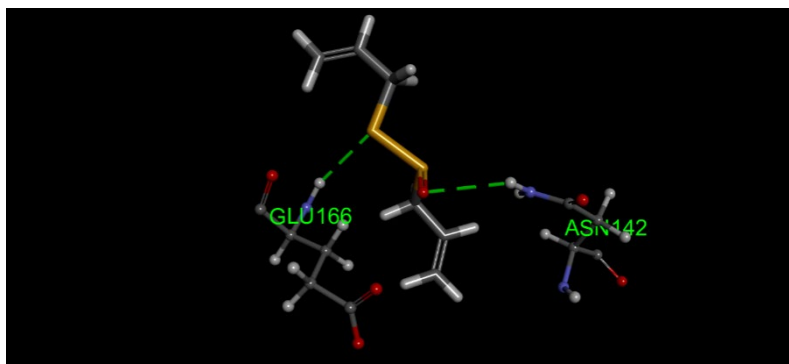
Figure 8. *The 3-D allicin ligand interactions on docking at the active site of the SARS-CoV-2 main protease*

Notably, the amino acid residues His163, Met49, and Met165 were found to participate in PI-Alkyl interactions with the ligand, while Glu166 and Asn142 were involved in conventional hydrogen bonding. Additionally, Arg188, Gln189, His164, His172, Phe140, Ser144, Leu141, and Gly143 were identified as key residues involved in van der Waals interactions with the ligand.

4. Discussion

SARS-CoV-2's main protease (Mpro), which is pivotal in the replication process of the virus, displays a highly preserved structure across numerous coronaviruses. This characteristic renders it an ideal target for potential antiviral strategies [20]. Interestingly, allicin - a prevalent organosulfur compound in garlic - has attracted substantial research interest given its extensive therapeutic benefits, which notably encompass potential antiviral properties.

The prospect of such a simple, commonly found compound interacting with a key viral protein presents a compelling direction in the search for effective and accessible therapeutics. In this context, our study endeavors to elucidate the nature of the interaction between allicin and Mpro, with an overarching aim of harnessing its potential for inhibiting SARS-CoV-2 replication.

Building on preliminary research suggesting an interaction between allicin and the catalytically active site of Mpro, we employed the CDocker method for in-depth molecular docking analysis. Our results demonstrate a robust interaction network between allicin and the active site of Mpro. This interaction network involves various amino acid residues crucial for Mpro functionality, specifically His163, Met49,

Met165, Glu166, Asn142, Arg188, Gln189, His164, His172, Phe140, Ser144, Leu141, and Gly143.

Detailed examination of these interactions suggests potential disruption in Mpro's functional mechanisms, namely substrate binding and dimerization, which is essential for its enzymatic activity [37]. In particular, His163, which is known to play a pivotal role in maintaining the correct conformation of the substrate binding pocket S1, was found to form PI-alkyl interactions with allicin [38]. The modification of His163 protonation state due to its interaction with allicin could significantly impact the conformation of the S1 pocket and the overall enzyme activity.

Additionally, allicin established conventional hydrogen bonds with Glu166, a crucial residue that connects the dimer interface and the substrate binding site. These interactions may trigger conformational modifications in Glu166, potentially disrupting the vital connection between the dimer interface and the substrate binding area [39]. This disruption might inhibit the formation of the active dimer structure, and as a result, compromise the enzyme's catalytic activity. Our docking studies show that allicin interacts strongly through a Glu166 NH⋯S hydrogen bond.

Less extensively studied residues, such as Met165, also interacted with allicin through PI-alkyl interactions. Despite a limited understanding of Met165's precise role, its interaction with allicin might have implications for the dimerization process of Mpro [40]. Lastly, Ser144 has also been identified to interact with allicin via van der Waals interactions. Prior studies highlight Ser144's critical role in stabilizing the dimeric structure of Mpro, and its interaction with allicin could destabilize this formation, thereby inhibiting the protease's functionality [41].

Collectively, these observations suggest that allicin's interaction with key residues in Mpro could potentially disrupt the enzyme's functionality, providing a rationale for further investigation of allicin as a potential Mpro inhibitor and consequently, a potential therapeutic against SARS-CoV-2.

5. Limitations

This docking analysis focused solely on evaluating the potential binding modes and critical residues involved in the allicin-Mpro interaction. Due to limited access to advanced modeling software and computation power, binding affinity quantification through CDocker scores was not feasible within the scope of this investigation. Follow-up studies utilizing more sophisticated software, larger computational capabilities, and additional modeling techniques could provide enhanced insights by yielding quantitative binding energy values.

By integrating advanced experimental and computational methodologies, future work can build on these preliminary findings to conclusively establish allicin as an inhibitor of the SARS-CoV-2 main protease. While the current analysis is an early step limited in scope, it offers a promising platform to guide further research on developing allicin as an antiviral therapeutic against COVID-19.

6. Conclusions

The discovery that a natural compound present in garlic can inhibit a vital viral protease presents a significant breakthrough in the field. This insight not only highlights allicin's potential as an antiviral agent but also sparks interest in exploring other natural compounds as possible countermeasures for SARS-COV-2 and related viral infections.

Our findings suggest a robust interaction between allicin and the active site of Mpro. Fundamentally, our study aids worldwide efforts to devise potent and all-

encompassing therapeutic approaches against the ongoing pandemic and prospective threats from coronaviruses. Subsequent studies aiming to experimentally validate allicin's binding to the Main protease would further substantiate our findings.

7. References

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Ad Infinitum: The Freedom-Centered Development of Human Rights Based on the Hegelian Speculative Philosophy of History

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Abstract

Human rights have lost their past reputation as a group of new scholars classified the end of the Cold War as the formal beginning of human rights, dismissing any connection between human rights and ancient philosophies or religions. Their arguments further called for human rights to retreat from the center stage and make space for substitute ideals before the entire system of distributive justice disappears. This research compares and contrasts one such scholar, Samuel Moyn's, proposition to German philosopher Georg Wilhelm Freidrich Hegel's Speculative Philosophy of History (SPH). Each phase that Moyn views as a false beginning of human rights is matched to a Hegelian phase of world history. Analyzing the two phases side-by-side reveals that each pair has the same level of consciousness of freedom, and as this consciousness grows, freedom is progressively closer to full actualization. Lastly, based on Hegel's view of continuous history rather than Moyn's dissociated history, this research outlines the future direction for human rights. This outline can enable human rights to become more universalized. The construction of a freedom-centered history of human rights upholds individuals' confidence in human rights and prompts them to actively improve the current conditions of human rights.

  Keywords: Human Rights; Philosophy of History; Freedom; Moyn; Hegel.

Introduction

"Human rights" is a household term in the status quo, but not necessarily a popular one. It emerges in most humanitarian non-governmental organizations' slogans and in international news, yet many have started to doubt if it still deserves its post-Cold War reputation. Recently, a group of scholars has argued that though human rights enable people to sympathize with strangers living abroad, they have turned a blind eye to the rising wealth inequality. One leading figure, Samuel Moyn, denounces human rights as a Western, Christian, and neoliberal mechanism that has minimal success in shaming state oppressors. His argument is contingent upon the revisionist

484

claim that human rights emerged *de novo* (anew or afresh) in the international community post-Cold War. [1] By dissociating human rights from the origins of religious tenets, natural law, and republican constitutions, he conveniently dethrones human rights from its moral high ground and labels it as Western political propaganda. As the ranks of the revisionists grow, the public's doubt of human rights slowly turns into antagonism.

Before the revisionists, it was rarely challenged that the universal right to freedom gave birth to modern human rights. Prescriptively, if not descriptively, human rights have always been understood to be universal entitlements that people had solely by virtue of their humanity. [2] Though not as preeminent in Platonic or Aristotelian ethics, rights and freedom first surfaced side by side in German idealism around the early nineteenth century. These philosophers did not construe freedom as a sanction for individuals to satisfy their animalities. Rather, freedom produces actions that are motivated by reason. In his essay *The Metaphysics of Morals*, Immanuel Kant calls freedom the "sole original right" and defines right as "the restriction of each individual's freedom so that it harmonizes with the freedom of everyone else (in so far as this is possible within the terms of a general law)." [3] Georg Wilhelm Friedrich Hegel uses a similar language in his *Encyclopedia*: Man can only be treated as free and as a person by obeying the universal will and behaving toward others in a manner that recognizes them as free and as a person. [4] However, Hegel moves beyond Kantian morality to the conception of the ethical life (*Sittlichkeit*), where concrete human actions actualize freedom. Unlike Kant, he places morality in the context of his SPH, which holds that historical stages advance where individuals gain increasing consciousness of freedom.

Since most scholars today support the German-idealist framework, they have long embedded freedom within human rights discourse. This approach simultaneously bolsters the fundamental nature of human rights as protection of freedom and condones its political implications. Regrettably, because existing literature uses freedom to justify only the status quo and not the continuum of human rights development, revisionists like Moyn took advantage and redefined human rights. Therefore, this study aims to fill this dearth by exploring the freedom-centered history of human rights. Applying Hegel's SPH can prove the continuity of human rights development from the past to the present and even into the future.

Using world history as the raw material from which human rights have progressed, this study will introduce and defend a freedom-centered framework for human rights history. This framework will recast past and current stages of human rights development as stages toward the ultimate actualization of freedom. Next, the paper will speculate on the future of human rights. The structure of this research will follow a direct comparison between each of Hegel's phases of history and the key junctures in human rights history that Moyn dismissed. This research will concentrate on Hegel's *Introduction to the Philosophy of History* and Moyn's *The Last Utopia: Human Rights in History*, but it will also include supplementary texts. Before synthesizing these two viewpoints, the first section will lay out the theoretical background guiding this research. The next five sections will address each stage of

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[1] Sarita Cargas, "Questioning Samuel Moyn's Revisionist History of Human Rights," *Human Rights Quarterly* 38, no. 2 (2016): 411.

[2] Laura Valentini, "Human Rights, Freedom, and Political Authority," Political Theory 40, no. 5 (July 12, 2012): 574, https://doi.org/10.1177/0090591712451721.

[3] Immanuel Kant, *Kant: Political Writings* (Cambridge, England; New York: Cambridge University Press, 2010): 136.

[4] Hegel, quoted in A. Honneth, *The Struggle for Recognition: The Moral Grammar of Social Conflicts* (Cambridge, MA: Polity Press, 1995): 108.

human rights development and the corresponding Hegelian historical phase. Then the paper will conclude with a discussion of this freedom-centered human rights history.

Theoretical Background

Hegelian SPH

The Hegelian SPH asserts that world history constitutes the course of the Spirit's realization of its ideal being, that is freedom, and culminates with freedom's complete actualization. First, Hegel deems reason and not chance as the driver of universal history. Because reason adopts the form of the World-Spirit, the world's ultimate design is then to fully manifest the Spirit's essence. [5] Thus, Spirit in its self-consciousness gradually produces more appropriate expressions and manifestations of freedom, enabling individuals to, in time, perceive themselves as a person possessing universality. If humans are considered to be the unity of mind and body, so too must Spirit eventually possess both self-consciousness and concrete embodiment. [6] Hegel prescribes no definitive time horizon, but rather posits this universal end as inevitable. He does, however, provide the process for freedom's actualization:

1) Spirit immerses in nature.
2) Spirit advances to the consciousness of its freedom.
3) Freedom elevates to its universal form and attains the consciousness and feeling of itself. [7]

The last stage corresponds to the fulfillment of *Sittlichkeit*. Ethical life, to Hegel, is superior to and inclusive of universal morality in the abstract, for "in the ethical realm, a human being has rights in so far as he has duties, and duties in so far as he has rights." [8] From these steps, Hegel then constructs his phases of world history. Each phase is distinguished by its new understanding of freedom, but these developments depend on the condition of freedom in the previous phases. These phases are:

1) Childhood in the ancient Oriental world;
2) Boyhood in ancient Greece;
3) Manhood in the Roman state; and
4) Old Age in the German world. [9]

It is this research's aim to demonstrate how these phases shed insight on the development of human rights. These phases' correlations to human rights history, the central content of later sections, are shown in Figure 1.

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[5] Georg Wilhelm Friedrich Hegel, *The Philosophy of History* (Kitchener, Ontario: Batoche Books, 2001): 30.
[6] David A. Duquette, "The Unity and Difference of the Speculative and the Historical in Hegel's Concept of Geist," *PhaenEx* 2, no. 1 (June 21, 2007): 90, https://doi.org/10.22329/p.v2i1.69.
[7] Hegel, *The Philosophy of History*, 72.
[8] Hegel, quoted in D. N. McNeill, "Social Freedom and Self-Actualization: 'Normative Reconstruction' as a Theory of Justice," *Critical Horizons* 16, no. 2 (May 21, 2015): 156, https://doi.org/10.1179/1440991715z.00000000045.
[9] Hegel, *The Philosophy of History*, 122-26.
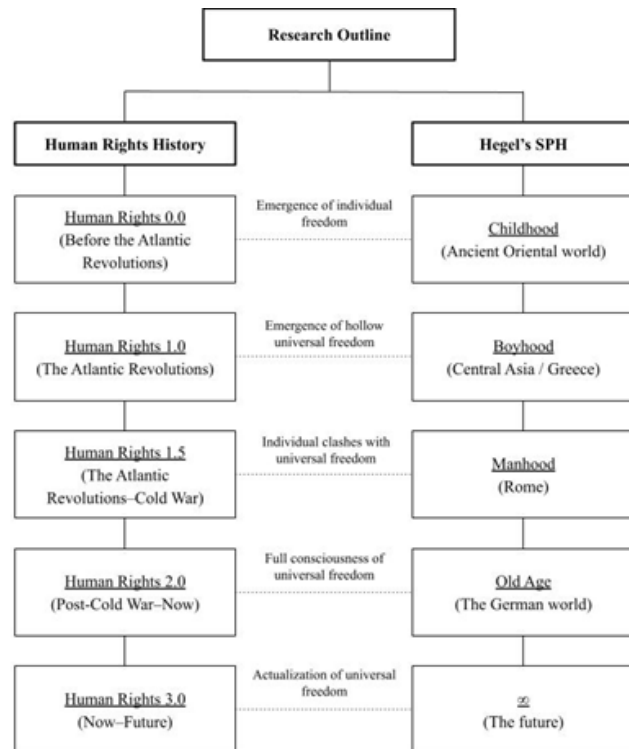
Figure 1. *Research Outline of the Correlation Between Human Rights History and the Hegelian SPH*

Moyn's Human Rights History

The precise origin of human rights has always been under debate, but researchers are unanimous that past religions and philosophies shaped breakthroughs like the Universal Declaration of Human Rights. Moyn counters their positions with French historian Mark Bloch's argument that just as floods depend on new sources where the river swells, continuity in history also depends on novelties.[10] Moyn takes a leap here by rejecting continuity altogether. The first claim of human rights' origin that he acknowledges is the period of the Atlantic Revolutions, what will later be referred to in this paper as Human Rights 1.0, yet he differentiates it from modern human rights because of its limited scope. He characterizes the other attempts to establish universal morality before or after the revolutions as vague and fickle. Modern human rights (2.0) then emerged. When Jimmy Carter proclaimed in his inaugural address "Because we are free we can never be indifferent to the fate of freedom elsewhere," human rights formally infiltrated the international agenda.[11] Moyn interprets today's human rights policies and actions as the ramifications of a Western savior complex. However, when

[10] Moyn, quoted in S. Mohney, "The Great Power Origins of Human Rights," *Michigan Journal of International Law* 35, no. 4 (2014): 830, https://repository.law.umich.edu/mjil/vol35/iss4/4.
[11] Carter, quoted in Samuel Moyn, *The Last Utopia: Human Rights in History* (Cambridge, MA: Belknap Press of Harvard University Press, 2012): 155.

matched with the aforementioned Hegelian phases, the historical nodes he dismisses become the building blocks for his Human Rights 2.0 and beyond.

Human Rights 0.0 (Childhood)

To Samuel Moyn, prior to the revolutionary era, Greeks, Jews, Christians, and philosophers created the false beginning of human rights. Although they all made references to humanity, they maintained exclusionary practices that contradicted the ideals they espoused. To Hegel, the phase of Childhood marked where history began. However, during this phase, the dawn of Reason bestowed upon individuals unreflective consciousness that could only sustain relations of "faith, confidence, obedience."[12] The religious and political conditions within this first pair of histories illuminate the emergence of individual freedom.

On Religion

Moyn criticizes that Christianity cannot serve as a model of universal morality because it has broken into different sects and changed rapidly throughout history. While Emperor Constantine ruled over a Christian Rome, today's Baptists, Lutherans, and Pentecostals debate over fundamental Christian principles. Different Christian universalisms cannot be universal, and Moyn warns of falling into this trap. When European travelers relied on their religion to interpret indigenous cultures, they made no breakthroughs for humanity.[13] Moyn recognizes regretfully that ideologies of Human Rights 0.0 have been integrated into the modern agenda. Since the twentieth century, Christianity has used God as a figurehead to frame human rights with Western interests. "Christian human rights were injected into tradition by pretending they had always been there, and on the basis of minor antecedents now treated as fonts of enduring commitments."[14] Varied Christian tenets, when associated with human rights, are both outdated and harmful.

A revelatory Christianity, in Hegel's perspective, commences the last phase of world history. Thus, the Christianity Moyn refers to—which condoned enslavement and violence—is more in conformity with Hegel's descriptions of African animism. In fact, Hegel notes that Childhood is largely unhistorical. The religious oppression Moyn alludes to evoke the Oriental sovereigns who enforce the moral and substantial. Individuals submit to that "One Individual" and seek dignity not in themselves but in that absolute object.[15] During the Zhou Dynasty in China, emperors indeed relied on the "Mandate of Heaven" to legitimize their rule, hence equating their authority with God's. These paternal governments utilized retributive or disciplinary inflictions to hold their constitutions, and in blind acceptance, the people had no purpose.[16] Notwithstanding, the subsequent section on the political condition clarifies the consciousness of freedom in this age.

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[12] Hegel, *The Philosophy of History*, 122.
[13] Moyn, *The Last Utopia*, 16.
[14] Samuel Moyn, *Christian Human Rights* (Philadelphia, PA: University of Pennsylvania Press, 2015), 5.
[15] Hegel, *The Philosophy of History*, 123.
[16] Ibid., 123.

On Empires

Prior to the Atlantic revolutions, all states were illiberal; they either contradicted or fell short of a true republic. Moyn denies any connection between these states' reign and the modern understanding of human rights. These states all employed forms of natural law, but natural law was subjective; it was "one rule given from above" that individuals had to obey.[17] Evidently, these states were not the ideal states, for they only granted humans the consciousness of torpid, limited freedom without subjectivity. Humans could only submit even if the law was unjust. This is why Kant asserts that perfect civil constitutions must adopt the form of a republic founded upon principles of freedom, dependence upon a common legislation, and legal equality.[18] Unfortunately, no state had adopted that form prior to the American and French Revolutions.

The correlation to the Hegelian phase is then not to states, but to empires. As Hegel considers the state to be the perfect shape that Spirit would adopt, the Oriental world clearly lacks the necessary consciousness of freedom. Consequently, Hegel summarizes the Oriental world as mere empires that occupied physical spaces. The "One Individual" posed as a patriarch and not a despot to the people. Having said that, Childhood is still worth mentioning because of its burgeoning thoughts of freedom. Due to incessant conflicts between the Oriental empires, opposing individualities first emerged, though they were unconscious.[19] Nonetheless, these individualities laid the groundwork for later universality. It is imperative to clarify that Hegel's concept of concrete universality does not reduce the particular to a common denominator; instead, it unites the particular without denying their differences.[20] Elements of the particular are bound to be excluded, but that is the cost of mutual recognition. Hegel's theory of mutual recognition entails the self becoming a particular in opposition to other particulars so that the self can let others be free rather than make slaves of others.[21] The later phases will demonstrate how this universality comes to pass.

Human Rights 1.0 (Boyhood)

Samuel Moyn dedicates this node to the revolutions that first appealed to freedom. However, because these nascent republics had a limited understanding of the protection of rights, the rise of modern human rights was fundamentally distinct. As for Hegel, he identifies the second phase of Boyhood as located in ancient Greece. Throughout the Greek city-states, there was a remarkable growth in individual will, but the unconscious still did not awaken. The revolutions and their byproduct illuminate the second pair's freedom.

On Revolutions

The first child of this era, in Moyn's perspective, is revolutionary rights. Whether in the Haitian Revolution or the thirteen colonies, their priority was to gain sovereignty and then to uphold human dignity. States and nations became the "crucible of rights,

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[17] Moyn, *The Last Utopia*, 30.
[18] Kant, 99.
[19] Hegel, *The Philosophy of History*, 124.
[20] Charlotte Baumann, "Adorno, Hegel and the Concrete Universal," *Philosophy & Social Criticism* 37, no. 1 (January 2011): 74, https://doi.org/10.1177/0191453710384362
[21] David S. Stern, ed., *Essays on Hegel's Philosophy of Subjective Spirit* (Albany: State University of New York Press 2013): 161. Accessed August 29, 2023. ProQuest Ebook Central.

and their indispensable ally and forum" to legitimize their own authorities.[22] As twentieth-century human rights focus on checking states' powers, revolutionary rights did not lead to the latter. Moyn's account gives the revolutions a different spin: the revolutionaries needed a license to instigate a conflict, and they found one in half-hearted appeals to European natural rights. Thus, the Declaration of Independence boldly claimed "that all men are created equal" yet meant quite the opposite. Other modern perspectives, though, believe that universal rights cannot exist without a political condition, for then there will be no agents to assume the role of protector.[23] Individuals will only seek their own passions. Accordingly, Moyn's Human Rights 1.0 and the establishment of republicans become a crucial step for human rights' later globalization.

Hegel regards revolutions not for the events themselves, but for their impacts on people. Wars and revolutions—of which Greece had many—alone produced no history. Yet humans possess a real capacity for change, a perfectibility, so institutional changes can move within humans and enhance their subjective freedoms. Like the Founding Fathers, the Greek philosophers advanced lofty ideals of freedom, ideals that mostly fell on deaf ears. Though morality started to take shape within individualities, Boyhood was the "Kingdom of Beautiful Freedom...the natural, unreflecting observance of what is becoming—not yet true Morality."[24] The heroic age of Greece only saw rulers who derived authority from their superiority in riches or ancestry. This kingdom is imperfect by Hegel's and Moyn's standards, except Hegel treats progress as the perpetual advancement from the imperfect to the perfect. For that reason, Hegel also calls the imperfect the so-called perfect, containing possibility points for the destined to become actual.[25] In the course of world history, freedom will often stumble and regress, but that is because the spirit must overcome formidable obstacles in order to make itself actually what it always was potentially.

On Citizenry

The second child is then citizenship rights. After justifying the revolution, rights proceeded to justify state-building and the centralization of power. They fabricated excuses for the creation or renovation of citizenship spaces over the protection of humanity.[26] The American Declaration defined inalienable rights available only to citizens. The French counterpart was called the "Declaration of the Rights of Man and of the Citizen," guaranteeing that "Men are born and remain free and equal in rights."[27] Sadly, both declarations failed to enforce the due treatment of "man" they propagated. As these new republics struggled to get a hold of themselves, they had limited resources, inducing them to favor those who had always been culturally and historically privileged. Therefore, the proposed "man" excluded the men without property; women; and non-humans, namely slaves and foreigners. Similar exclusions were found in Greece.

Hegel believes that Greek freedom only existed in ideology and not practicality; it was charming but perishable. Philosophers certainly elevated their consciousness of freedom, yet the same did not apply to the rest of the population.

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[22] Moyn, *The Last Utopia*, 23.
[23] Valentini, 576.
[24] Hegel, *The Philosophy of History*, 124.
[25] Ibid., 73.
[26] Moyn, *The Last Utopia,* 35.
[27] "Declaration of the Rights of Man – 1789," Yale Law School The Avalon Project (2019), https://avalon.law.yale.edu/18th_century/rightsof.asp.

While the Orientals lived as "One is free," the Greeks lived as "Some are free."[28] The majority still adopted unreflectively the prescriptions of justice and law. The slaves were denied their due freedom, but they did not challenge the oppressive conditions, for they did not think these conditions were wrong. Speaking of the Greeks, their "free spirits have not yet appreciated its infinity. Man is only free within nature and remains restrained within nature."[29] Rather than despair, Hegel once more treats this "Kingdom" as an inevitable occurrence of the spirit self-negating to become a purer version of itself. So for Greek city-states or absolute monarchies with limited legal protections, they were mere partial stations on the road to the final reconciliation of ethical life.[30]

Human Rights 1.5 (Manhood)

Moyn moves on to challenge the alleged connections between human rights and the two centuries between the revolutions and the present. He criticizes rights of this era for their domestic scope and ambiguity. On the other hand, Hegel's phase of Manhood is born in the Eternal City, Rome, and it highlights the process of individualities coalescing to the universal. Both of Moyn's criticisms and the anticolonial sentiments after WWII illuminate the progressed freedom from the previous stage.

On Civil Liberties

Civil liberties are often confused with human rights. While human rights apply to all humans, civil liberties stop at national borders. Champions of civil liberties are unavoidably tangled with politics as these liberties simply inherited and polished up revolutionary rights that mandated membership in society. Such liberties premised themselves on the nation-state and "rooted their claims not in universal law but in allegedly deep national traditions of freedom."[31] That, to Moyn, is antagonistic toward the contemporary ideals of curbing state sovereignty. Putting his viewpoints aside, though, it is noteworthy that the rise of civil liberties did enable minority groups to voice their grievances. Furthermore, more often than not, one civil rights movement would inspire another across the ocean, causing more countries to extend citizenship to previously marginalized groups.

For Hegel, his philosophy of rights actually terminates at the nation-state level, which would correspond to civil liberties, but Human Rights 1.5 has not yet attained ethical life. The third stage of Rome aligns here because it is when the state first acquires abstract existence. Since states lose all authority without adequate protection of rights, revolutions and lofty declarations did not grant them legitimacy, but the specification of rights did. The United States, for example, has undergone a series of specifications from the Bill of Rights to the Civil Rights Act of 1964. As the government takes on additional roles, the people also give away parts of their individual will. Hegel bluntly states that with the contention of private interests, they must ultimately become one with the interest of the State.[32] This is the process of perfecting a republic so that members can elect a representative to decide on their behalf, as occurred in Rome.

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[28] Hegel, *The Philosophy of History*, 33.
[29] Stern, 158.
[30] Costas Douzinas, "Identity, Recognition, Rights or What Can Hegel Teach Us about Human Rights?," *Journal of Law and Society* 29, no. 3 (September 2002): 381, https://doi.org/10.1111/1467-6478.00225.
[31] Moyn, *The Last Utopia*, 38.
[32] Hegel, *The Philosophy of History*, 39.

On Ambiguity

Moyn's second criticism is the lack of consensus on the definition of human rights, creating situations where rights claims frequently become akin to magical commands. As late as Franklin D. Roosevelt's times, the definition of human rights was rhetorical and "amounted to no more than an anarchic cacophony, in which earlier competing ideals were reformulated in new language."[33] As mentioned previously, people did not have a precise understanding of past ideals, so an advocate could invoke natural rights while circuitously promoting and defending capitalist rights. Without set parameters, European conservationists developed their highly Christian version of human rights, Americans developed their version, and Latin Americans developed another. Amidst this chaos, it would truly seem that "human rights were the victims of their own vagueness."[34]

Hegel presents more nuanced views. Regarding ambiguity, Spirit is never fully aware of its ultimate goal when it is in the middle of history, but by making war upon itself, Spirit works up the existence to a purer form. Karl R. Popper, a critic of Hegel, defined history as a process of social development that learned from prior mistakes through "trial and error" or "conjecture and refutation."[35] But the Hegelian thought does not stray far. As the Spirit hides itself, world history is in a perpetual cycle of trial and error, of locating what has betrayed expectations then making corrections. In Rome, individuals have gained subjectivity, but self-control and self-organization are still hidden to them. Consequently, without more attempts, many of which will be unsuccessful, humans will only dwell within this consciousness of freedom that is short of the universal form.

On Anticolonialism

Post-WWII, one of the most important items on the United Nation's agenda was decolonization. After some debate, world leaders agreed that self-determination should be given to all colonies and not just territories held by the Axis Powers. According to Moyn, this was the closest call but still not human rights. With the strong anticolonial sentiments then, the only interference of sovereignty allowed was when the violation concerned "white men's imperialism."[36] The newly independent states, mainly the Afro-Asian bloc, started voting in alignment with their interests while the old Western powers voted to preserve their authority. Gridlocks made it impossible for states to agree on any universal truths. And, within this surge of anticolonialism, imperialism still survived. The end of King Leopold II's rape of Congo was known as the "first great human rights movement of the twentieth century."[37] Moyn rejects this positive assessment because the allegedly instrumental activists had only re-allocated Congo from Leopold to Belgium's rule. Ultimately, self-determination failed to limit state sovereignty on the same level as modern human rights.

Hegel's Manhood identifies a mismatch between the universal and the particular. Though individuals have discarded their own or a despot's caprices, they are still subjugated under the universal. As seen during Human Rights 1.5, each state desperately tries to champion their favored versions of human rights in fear that they

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[33] Moyn, *The Last Utopia*, 52.
[34] Ibid., 64.
[35] Frank Ankersmit, "The Thorn of History: Unintended Consequences and Speculative Philosophy of History," *History and Theory* 60, no. 2 (June 2021): 198.
[36] Moyn, *The Last Utopia*, 94.
[37] Samuel Moyn, "Human Rights and the Crisis of Liberalism," (Cambridge: Cambridge University Press 2017): 269.

would be crushed, buried, and incorporated with the homogeneous mass. Hegel promotes an elevation to universal morals, but that requires free will. Individuals must willingly choose to adopt principles that tend to the good of all in order to achieve spiritual pacification, and he designates this decision as the mechanism to move from Manhood to the subsequent phase.

Human Rights 2.0 (Old Age)

At last, Moyn acknowledges the end of the Cold War as a trigger for modern human rights, but as the United States framed human rights as a foreign policy, it sowed the seeds for contemporary problems like wealth inequality and human rights' lack of enforcement. Hegel's Old Age necessitates the spirit's perfect maturity, a complete consciousness of freedom, and his historical example is the formation of the Germanic state. Since this final pair denotes the present, evaluating successes and failures in the status quo illuminates how freedom is perceived and exercised.

On Successes

At the root of his arguments, Moyn recognizes some of the good human rights have brought, and he credits non-governmental organizations far more than state actors. For example, Amnesty International stood up for legalization and better enforcement of human rights laws. NGOs are also effective at curbing rights inflation. The tendency to define anything desirable as a right is dangerous because it "cheapens the human rights tradition, erodes consensus on rights, dilutes the moral power of rights, and weakens enforcers' will."[38] At the same time, though, NGOs are gatekeepers who enable new grievances to be brought to the table. Once NGOs realized that the UN is not the best forum for human rights activism, they started mass participation through their local chapters.[39] Arguably, they exerted the pressure on governments to engage in sanctions and shaming mechanisms, bringing scrutiny to state violences. Transparency, though incomplete, was human rights' most transformative impact on the modern world. A reason why people think there are more human rights violations today is because people are better informed.

Hegel's fourth phase begins with a Christian reconciliation. The ecclesiastical, Hegel writes, holds the true content of the Spirit, but it requires other institutions to realize this freedom, so the state will eventually embody the church. It is crucial to interpret this point apart from a theological mindset. The Hegelian spirit moves from nature, which is man's point of departure, to God, which is man's final purpose.[40] Thus, the definitive consciousness that the Germans attained is that "man, as man, is free."[41] This is the reconciliation between the spiritual, the religious, and the barbarian secular world. Both Kant and Hegel defined freedom as recognizing the existence and need of others. The full consciousness of freedom resides in relations of mutual recognition between individuals, between the state and the people, and between the universal and the particular. Hegel's theory on rights concludes at the state level, but because order can only exist in states, all international affairs become the relations between states.[42] Though this belief differs from Kant's formal

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[38] William Alston, quoted in C. Bob, ed., *The International Struggle for New Human Rights* (Philadelphia, PA: University of Pennsylvania Press, 2010): 11.
[39] Moyn, *The Last Utopia*, 130.
[40] Hegel, quoted in Stern, 159.
[41] Hegel, *The Philosophy of History*, 33.
[42] Andrew Vincent, "The Hegelian State and International Politics," *Review of International Studies* 9, no. 3 (July 1983): 191, https://doi.org/10.1017/s026021050011589x.

endorsement of an international federation, it appropriately prescribes the states' responsibilities in terms of human rights. The states' internal and external relations create their responsibilities to their citizens and to all humans.

On Failures

Moyn's attacks on contemporary human rights are numerous. The gatekeepers that he lauds are frequently motivated by political agendas, hence orienting modern rights in a Western and neoliberal direction. Most NGOs and governments today also ignore social and economic rights, attracting Moyn's criticism, "with their focus on ensuring a bare floor of material protection for individuals in a globalized economy, human-rights movements did nothing to prevent the obliteration of a wealth ceiling."[43] States do not always ensure even that minimum material protection. However, exploring the relationship between human rights and economic equality is outside of this paper's subject. Another and perhaps most often cited criticism of international human rights is its lack of enforcement. Even today, human rights norms continue to be aspirational, "enforcement mechanisms are toothless," and "treaty regimes are notoriously weak." [44] Shaming mechanisms and sanctions are only useful when human rights perpetrators decide to acquiesce, and political interests often deter states from denouncing trade partners with unsightly human rights records.

Considering the stagnant Human Rights 2.0, it begs the question of whether or not spirit is fully actualized. The old age of nature is, after all, weakness in contrast to the spirit's perfect maturity.[45] It would seem that with Human Rights 2.0, or the German world, people merely attained full consciousness of freedom but not its full actualization. Knowing one's essence is free is different from being free. Referring back to Hegel's hierarchy of rights, where consciousness transitions into concretization marks where ethical life begins. On that note, as iterated by renowned human rights professor Costas Douzinas, at present, human rights are still struggling to balance the universal and the particular:

> "Human rights-claims, therefore, involve a paradoxical dialectic between an impossible demand for universal equality, initially identified with the characteristics of western man, and an equally unrealizable claim to absolute difference. Because the nature of western, white, affluent man cannot subsume under its universal aspirations...the claims to specific workers', women's or ethnic rights arises."[46]

Hegel has also addressed the lack of enforcement of shaming mechanisms. In his *Phenomenology of Spirits*, he calls the self-serving, judgmental consciousness the "Beautiful Soul," a spirit that plays moral valet in order to absolve itself from culpability. [47] For the states who only point the finger, they think they occupy a position of moral excellence when, in reality, they are also guilty of inaction. Some call the Beautiful Soul a symptom of secular morality and its privatized ethics.[48] These

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[43] Samuel Moyn, "Human Rights Are Not Enough," The Nation, March 16, 2018, https://www.thenation.com/article/archive/human-rights-are-not-enough.
[44] Harold H. Koh, "How Is International Human Rights Law Enforced?," *Indiana Law Journal* 74, no. 4 (1999): 1398.
[45] Hegel, *The Philosophy of History*, 126.
[46] Douzinas, 400-1.
[47] Georg Wilhelm Friedrich Hegel, *The Phenomenology of Spirit* (University of Notre Dame Press: 2019): 333.
[48] Drew Milne, "The Beautiful Soul: From Hegel to Beckett," *Diacritics* 32, no. 1 (2002): 65, https://doi.org/10.1353/dia.2004.0016.

souls' judgments exacerbate the disorders they condemn, for they turn the perpetrators into hypocrites who could find selflessness motivating their violations. The Beautiful Souls' extreme self-consciousness further indicates that the Spirit is not yet at its perfect strength.

Human Rights 3.0 (∞)

This freedom-centered framework does not and cannot end in the present because human rights have not yet entered ethical life and the essential destiny of Spirit is still an unreality. Considering the many defects of modern-day human rights, there is ample room for growth, for human rights to expand their scope, curtail state violations, and become universal. This section will justify human rights' continuous development before exploring how human rights can perfect themselves.

On Continuity

Moyn urges that modern human rights cannot continue as they are, and humans were wrong to treat these ideals as the panacea to all suffering, but he diverges from Kant or Hegel in believing that human rights cannot improve or reinvent themselves; they must give way to something entirely new.[49] The future he envisions is characterized by the same concept of discontinuity that he has applied to the nodes of human rights development. Since human rights started off as post-Cold War propaganda, its continuation will destroy distributive justice. On Moyn's standpoint, Hegel does regard poverty as a failed form of legal recognition because it drives one's self-consciousness to the extreme, which is precisely why ethical life, whose actualization demands mutual recognition, would prevent this.[50] Though Hegel provides no explicit solution to poverty, his SPH champions the process of trial and error to find a solution.

Both Kant and Hegel believe in the continuation of the imperfect status quo, only by different methods. While the phrase Old Age carries a sense of closure, Hegel concludes the section with "Yet length of Time is something entirely relative, and the element of Spirit is Eternity."[51] It is more apparent in the present that the German world had achieved its purpose, then declined; Human Rights 2.0 will also reach its end, but until the full consciousness of freedom manifests, world history will continue. Kant's method prescribes approximation to the ultimate goal. In his own speculative history, he explains that the precise time at which the achievement of this end will occur "must remain indefinite and dependent upon chance."[52] While he disbelieves in complete realization and actualization, he is hopeful that man will be able to get infinitely close to the goal. Although Kant compares mankind's progress to that of Sisyphus, who often takes one step forward and two steps back, Hegel equates historical development to a phoenix's rebirths, where the Spirit will only realize itself into purer and purer forms.

On Advancement

By Moyn's account, human rights ought to make room for socialist ideals and

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[49] Moyn, "Human Rights Are Not Enough."
[50] Douzinas, 395.
[51] Hegel, *The Philosophy of History*, 128.
[52] Kant, 185.

movements that will focus on bridging the wealth gaps. Since his "Human Rights 3.0" would require pushing human rights to the sidelines, it is important to reflect on other scholars' proposed mechanisms for breakthroughs in human rights. Many emphasize the need to treat civil, political, economic, social, and cultural rights equally. After all, states have an obligation to ensure negative and positive rights, such as taking active steps to curb threats to freedom. Most of their research explores new territories of human rights, such as broadening the paradigm to create new rights for robots.[53] The need for new rights, either omitted by international law or codified but never fully upheld, is critical, and the creation of such rights will involve everyone from the claimants to the NGOs to state actors.

All these proposals, however, still leave a gaping question unanswered: how can human rights be better enforced? While Hegel does not address this problem directly, he explains the more affirmative approach of how to elevate the world's current understanding of human rights. Hegel deems action as the means to actualize a mode of knowing to reality that has been brought about by consciousness.[54] Those "Beautiful Souls," the states preoccupied with shaming other states, could have done something while they were drafting speeches to denounce other state oppressors. Sovereignty often deters international intervention, despite the fact that a state only has the right to govern undisturbed as long as it protects human rights. The moment the state fails, it loses part or all of its moral standing from within and from the outside.[55] In fact, action is the only determinant through which freedom can be fully actualized. Hegel writes, "To act is then merely to translate the self's individual substantive content into the objective element in which it is public and is there to be recognized; and the fact that this content is recognized is precisely what makes that action real." [56] This marks another divergence between Hegel's and Kants's philosophies on rights. Kant believes that observing catastrophes from a distance generates beauty, leading to a universal yet disinterested sympathy that proves mankind's moral character.[57] In other words, he would only criticize the states in the status quo for their partiality but not their spectating of world tragedies. Hegel, on the other hand, calls for states to be impartial and active. Beauty can only be attained by the full actualization of freedom, which necessitates dirtying one's hands through action. While on an individual level, certain actions are limited by the availability of resources, on a state level, taking action is synonymous with making a choice between prioritizing state sovereignty or the universal moral obligation.

Discussion

As the analysis demonstrated, Moyn's human rights history and Hegel's account of world history are very similar. The degree of freedom each phase of history has is highly compatible, but what sets them apart is the nuance of continuous or discontinuous history. While Nietzsche praises forgetting like the animal and living unhistorically, Moyn's perspective is closer to one of dissociation from the past.[58] Other revisionists interpret Moyn's perspective in various facets. Anton Froeyman's

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[53] Alexandra Huneeus, "Symposium on the Universal Declaration of Human Rights at Seventy Human Rights and the Future of Being Human," *Cambridge University Press*, 2018, 324-5, https://doi.org/10.1017/aju.2018.90.
[54] Hegel, *The Phenomenology of Spirit,* 346.
[55] Valenti, 588.
[56] Hegel, *The Phenomenology of Spirit,* 349.
[57] Kant, 182.
[58] Friedrich Wilhelm Nietzsche, *On the Advantage and Disadvantage of History for Life.* (Hackett Pub. Co., U.S, 1980): 9.

moral anachronism describes how remnants of the past—institutions, norms, or traditions—continue to exist, but the moral values they were once erected upon are long gone. [59] Reverse-engineering this will lead to Moyn's conclusion that revolutionary rights, civil liberties, and self-determination took turns to validate universal morality, and now, human rights have picked up the baton. Yet Dutch philosopher Frank Ankersmit initially believed that forgetting a previous world and shedding a former identity would enable entrance into a new world. [60] Two decades later, he reasoned that Hegel's SPH is the wisdom of how to situate past knowledge in the present. Moyn's perspective, through forgetting and overlooking parts of the past, causes these parts to remain with individuals and prevent individuals from acquiring a new historical sensibility. [61] The revisionist viewpoint inhibits the attainment of Human Rights 3.0 because it envisions a new world and not a better world.

Growth is much better represented by Hegel's SPH. According to him, history and everything in it—art, religion, science—is highly mutable, but their essences remain the same. He asserts that "the individual traverses as a unity various grades of development, and remains the same individual; in like manner also does a people, till the Spirit which it embodies reaches the grade of universality." [62] Hegel would not challenge the fact that human rights had undergone all kinds of upheavals along the path of their development. He would reiterate that despite these changes, human rights remain the same idea but become better with more consciousness of freedom. Freedom's development works in the same way. When individuals have a taste of abstract freedom, they will want more, eventually producing universal freedom that harmonizes with others' needs. It is just like a teenager who received permission to go out with his friends. He will then want a car to make this freedom a reality, but his acquisition of this car might make him responsible for driving his siblings to school.

With Hegel's analogy for the phases of world history, there is one last approach to understanding a continuous SPH. The names "Childhood," "Boyhood," "Manhood," and "Old Age" mimic a person's maturity. Any individual could say that they have changed drastically from when they were a baby, but that does not signify they have become a completely dissociated being from whom they were back then. Similarly, human rights have undergone an evolution into their present forms. SPH sets up the foundation needed for future improvements as demonstrated in the following historical example:

> "There is nothing necessarily wrong with predicting the future. Astronomers do so all of the time. They tell us, for instance, that the Sun's luminosity increases by one percent every 110 million years and that it will be thirty-three percent more luminous in 3 billion years. In about 7.5 billion years, the fate of Earth will be sealed through its absorption in the Sun. Future astronomers may revise the details of these predictions, but the substance of this sketch of our planet's future will not change." [63]

SPH is not about making wild guesses about the future. These speculations

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[59] Z. B Simon, *History in Times of Unprecedented Change: A Theory for the 21st Century* (Bloomsbury Academic, 2019): 12.

[60] Frank Ankersmit, "The Sublime Dissociation of the Past: Or How to Be(Come) What One Is No Longer," *History and Theory* 40, no. 3 (October 2001): 301, https://doi.org/10.1111/0018-2656.00170.

[61] Ankersmit, "The Thorn of History: Unintended Consequences and Speculative Philosophy of History," 212.

[62] Hegel, *The Philosophy of History*, 95.

[63] Ankersmit, "The Thorn of History: Unintended Consequences and Speculative Philosophy of History," 197.

create the paradigm for how to bring world history one step closer to ethical life. The Human Rights 3.0 section follows this same doctrine of SPH to pose conjectures on the future directions of human rights.

Conclusion

Based on Hegel's SPH, it is evident that human rights' history is continuous; each phase is a historical node during which freedom can actualize to full consciousness. Sometimes, the historical development of freedom might regress, but even then, each event happens for the aforementioned purpose. This understanding counters the revisionist view, preventing individuals from dismissing any stage of human rights' past. Human rights' philosophical, religious, and political roots thus give people the assurance that human rights are inherently grounded in ideals of morality and political freedom. This assurance is critical, for the erosion of trust is already manifest. Countries around the world have taken steps to inhibit NGOs from working at full capacity and, in extreme cases, expelled them. The roots of human rights also help people appreciate the good works these rights have already done for the world. If human rights were to disappear, then these benefits would lose their effectiveness. States could wantonly violate rights without concerns of sanctions or international condemnation. There would be no robust civil society to take in refugees or asylum seekers. Therefore, it is crucial for people to keep the ultimate goal—the actualization of universal freedom—in mind and maintain faith in human rights.

Another section of this research presents the speculative future for human rights. These rights must shift from stagnant international rules to enforceable laws, and from inaction to action. This is both necessary and inevitable. Let the findings of this research also serve as a timely reminder for supranational organizations, states, NGOs, and individuals to proactively take human rights to the next level rather than dwelling in the current stage and lamenting their shortcomings. States have the obligation to act affirmatively, but so do individuals who wish to obtain true freedom. The formation of any new right begins from the bottom, from the people, which is why the people ought to believe in human rights' potential for change. The people must also seek fuller consciousness of freedom so that they can recognize their moral duties to those who live an ocean away: the stateless population, or immigrants living in the country's shadowy corners.

Limitations and Future Study

By focusing on the larger framework of a freedom-centered human rights history, this research could have glossed over certain nuances within each historical phase. One minor discrepancy mentioned was the birth of Christianity that emerged in polar opposite phases within Moyn and Hegel's accounts. However, since both histories were examined solely for their degrees of freedom, the discrepancies make little impact. Having said that, it will be worthwhile for future research to look at applying Hegel's SPH to the development of art, religion, or science. Another significant area needing more research is the future of human rights and how Hegel's call for action can appeal to states, prompting them to utilize their freedom of reason and correct their self-serving "Beautiful Souls."

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✵

A Meta-Analysis of the Effect of Right-to-Work Laws on Labor Unions and Workers

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Abstract

Intense discussions over labor policy have been triggered by the implementation of right-to-work (RTW) laws in the United States. From the economic perspective, this paper ultimately concludes that RTW laws tend to decrease the wages of average workers and raise the employment rate. Although proponents contend that RTW laws promote workers' autonomy, this paper finds that they weaken union power and harm workers' well-being. This paper contributes to the existing body of knowledge by analyzing prior theories and data analysis to offer information about the effects of RTW laws.

1. Introduction

The implementation of right-to-work (RTW) laws in the United States has sparked intense debates within the labor policy realm. These laws grant employees the right to work in a unionized workplace without being obligated to join or financially support the union. Policymakers, labor unions, and business interests have all been drawn to these laws due to their significant impact on unionization rates, wages, and overall employment. For anyone interested in labor relations, worker rights, and understanding the broader economic landscape, it is crucial to comprehend the implications of RTW laws.

RTW laws have significant implications for workers' rights and freedom of choice. Those in favor argue that these laws protect individual autonomy by allowing workers to decide whether to join a union and financially contribute. They believe that forcing workers into union membership infringes upon their independence and ability to make independent choices. However, opponents of RTW laws argue that they weaken unions, reducing their effectiveness in representing workers and diminishing collective bargaining power. Critics claim that this can result in lower wages, deteriorating working conditions, and ultimately harm the overall well-being of workers.

This study particularly examines the economic effects of RTW laws on wages and employment. It draws from the extensive previous research and comprehensive data analysis conducted during my debate career. Both the positive and negative literature are assessed in this paper, and certain theories are organized as counterarguments to other plausible explanations. The goal of this paper is to provide valuable insights into the existing body of knowledge.

2. Background

The National Labor Relations Act (NLRA) enacted in 1935 serves the primary purpose of regulating private sector unionization and collective bargaining. The legislation permits

union security agreements between employers and labor organizations that enforce union membership and the payment of union dues.

However, in 1947, the Taft-Hartley Act amendments to the NLRA eased this enforcement, as individual states were given the option of prohibiting these union security agreements, even for workers that benefit from provisions negotiated in the collective bargaining agreement (CBA). These state laws are known as *right-to-work* (RTW) laws. As of today, twenty-eight states are RTW states, all of which are heavily concentrated in the southern and southwestern United States.[1]

Additionally, the US Supreme Court's rule of the *Janus v. American Federation of State, County and Municipal Employees* (AFSCME) in 2018 resulted in concerns that challenge the legality of forcing public employees to pay union dues, despite declining union membership. The case ruled that the mandatory payments had violated the First Amendment of the US Constitution since part of the union dues went to supporting the union's political activities. The *Janus* decision has blocked all possible ways for public sector unions that attempt to distinguish between political and apolitical union activity to influence government.[2]

Figure 1. *Current demographic depiction of the 28 RTW states (NRTWLD&EF 2023)[3]*

3. Method

This paper utilizes a systematic approach to analyze and evaluate existing literature on RTW laws. It specifically focuses on assessing the effectiveness of their approaches and the logicality of their theories. A comprehensive review will be conducted, encompassing relevant scholarly articles, reports, and academic publications. Multiple datasets relating to RTW laws, unionization, wages, and employment will be utilized. The findings from these studies will be synthesized and discussed to identify patterns, inconsistencies, and gaps in the literature concerning RTW laws, unionization rates, wages, and employment. The implications of these findings will be considered within the broader context of RTW laws by highlighting areas for further research and contributing to existing knowledge in this field.

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[1] *Right to Work States | UpCounsel 2021.* (n.d.). UpCounsel. https://www.upcounsel. com/right-to-work-states

[2] Scimecca, James. *"The Janus Effect."* Empire Center for Public Policy, 21 Feb. 2023, www.empirecenter. org/publications/the-janus-effect/.

[3] *Right to work states.* National Right to Work Foundation. (2023, November 17). https://www.nrtw. org/right-to-work-states/

4. Literature Review

There has been a significant amount of debate on the impact of RTW laws on workers through economic and social aspects. Although most research shows that RTW laws have a negative correlation with unionization rates, it is difficult to establish a causal relationship between unionization rates and RTW laws. Similarly, when it comes to outcomes such as employment and wages, studies have produced conflicting results, largely due to variations in research methodologies. This paper will provide a summary and analysis of the existing data and scholarly research on RTW laws, which often present conflicting findings. It will also cover well-developed theories and highlight several comprehensive studies that attempt to account for other factors and isolate the specific impact of RTW laws.

4.1 RTW Laws and Unionization Rates
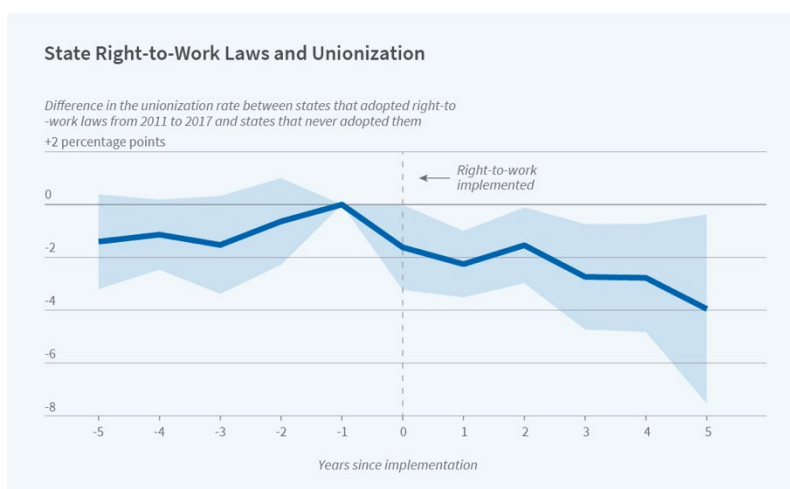
Figure 2. The trend of RTW laws and unionization rate (Page 2022)[4]

To explain the decreasing trend of unionization rates following the implementation of RTW laws in different states, researchers have presented specific data that supports their hypotheses, among which two of most commonly cited will be discussed below.

The most well-known hypothesis may perhaps be the *free-rider hypothesis:* Under RTW laws, workers are not forced to pay union dues, which will lead to an increasing number of workers choosing to enjoy the benefits of being covered by a collective bargaining contract without paying their fair share of union dues. A vicious cycle could occur, leading to spiraling high dues for the remaining dues-paying members. The increased dues may surpass the willingness of the remaining members to pay for representation, resulting in a situation where more workers choose to stop paying dues. This can eventually lead to an unsustainable burden on the remaining members and a decline in representation quality due to the lack of available funds.

However, supporters of RTW laws may also claim that RTW laws can increase the need for unions to demonstrate their effectiveness by securing benefits to earn union dues, thus providing members with better overall representation. The quantitative evidence for both sides of this hypothesis will be evaluated based on economic and social outcomes later in this paper.

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[4] Page, L. (2022, August 8). *Impacts of Right-to-Work Laws on Unionization and Wages.* NBER. https://www.nber.org/digest/202208/impacts-right-work-laws-unionization-and wages

Supporting the free-rider hypothesis, researchers at the University of Illinois at Urbana-Champaign have found that RTW laws lower a worker's probability of being a union member by an average of 9.9 percent, after accounting for different variables and limiting the research to the working-age employed population. They categorize their studies with different variables in a table:

Table 1. *Categorization of different approaches towards RTW effects on the probability of being a union member (Bruno et al. 2015)*[5]

RTW Effects on the Probability of Being a Union Member			
Effect	No Controls	All Controls	Controls with State Effects
RTW effect	-9.7%	-9.9%	-1.5%
Recession		0.6%	0.6%
Recession, RTW state		-0.4%	0.0%

In a study conducted by Sobel in 1995[6], nonpaying workers covered by unions were categorized into two groups: "true free riders" and "induced free riders." The former group consisted of individuals who valued union representation and would willingly join the union if dues were mandatory, while the latter group comprised individuals who did not place value on representation and would seek alternative employment if dues were compulsory. The study estimated that in states with RTW laws, approximately 70 percent of free riders fell into the induced category. This finding challenges the notion that the presence of RTW laws solely attracts individuals who wish to benefit from union representation without paying dues, known as "true free riders." Instead, the study suggests that a majority of nonpaying workers in RTW states have no interest in union membership or the associated benefits. Therefore, if workers were given the option to legally unbind themselves from the CBA, unions could, to the least extent, lose only 30 percent of dues *per represented individual*. However, that is not the case at present.

A complementary hypothesis to the free-rider hypothesis is the *bargaining power hypothesis*, which asserts that RTW laws reduce the bargaining power of unions in the long run due to fewer members and fewer union dues. As a result, unions have less incentive, financially, to organize bargaining activities.

Ellwood and Fine, in their 1987 study, used union elections data to go back in time and estimate the effect of the introduction of RTW laws between 1951 and 1977. They found that five years after the passing of RTW laws, union organizing activities fell by 28% and organizing success also fell by 46%.[7] In addition, it led to a 5-10 percent decline in the rate of unionization in the long run.[8]

Furthermore, by comparing data from five states, researchers from the National Bureau of Economic Research found that RTW laws are associated with a 4 percent drop in unionization rate five years after adoption. They found that these impacts are mostly driven by the construction, education, and public administration industries that have had a high unionization rate. Another approach can be used where they assume that without RTW laws, all states have the same relative distribution of unionization rates and wage levels across industries. The result is a nearly 20 percent difference in the unionization

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[5] Bruno, Robert, et al. "The Economic Effects of Adopting a Right-To-Work Law." *Labor Studies Journal, vol. 40,* no. 4, Dec. 2015, pp. 319–361

[6] Russel Sobel, "Empirical Evidence on the Union Free Rider Problem: Do Right-to-Work Laws Matter?," *Journal of Labor Research*, Summer 1995, pp. 347-365.

[7] David Ellwood and Glenn Fine, "The Impact of Right to Work Laws on Union Organizing," *Journal of Political Economy,* April 1987, pp. 250-273.

[8] Another study conducted by Moore, W. J., J. A. Dunlevy, and R. J. Newman in 1986, named "Do Right to Work Laws Matter? Comment" finds a similar result: by surveying accumulated evidence from the past, RTW laws have a significant negative effect on union organizing in the short term and reduce long-run unionization rates by 5 to 8 percent.

rate between RTW states and non-RTW states.[9]

4.2 RTW Laws and Wages

In the economic aspect, RTW laws also greatly alter the wages of workers. Most results support the theory that a decline in unions would lead to lower wages for the average worker group due to fewer attempts at or successful negotiations between employers and employees, with a few expectations suggesting either no relationship or a positive relationship between RTW laws and worker wages. However, most studies, like Moore (1980), Wessels (1981), Moore et al. (1986), and Hundley (1993) find no effect when only comparing cross-state differences at a specific point in time. This is primarily because there were very few adoptions of RTW laws between 1963 and 2001, with only two exceptions: Louisiana in 1976 and Idaho in 1986.

Gould and Kimball (2015) claim that it is hard to isolate the causal effect of RTW laws on wages and most of the research done before was based on a cross-sectional approach to determine correlations. Nevertheless, their research indicates that salaries in states with RTW legislation were reduced by 3.1 percent compared to states without such laws, even when accounting for various individual demographic and socioeconomic factors, as well as statewide economic indicators. This 3.1 percent decrease can equivalently be expressed as RTW statutes being linked to a $1,558 decrease in yearly earnings for an average full-time, full-year employee.[10]

In terms of the growth of wages, Chava et al. (2020) conducted a study using wage growth data from 19,574 CBAs in five different states during the years 1988-2016: Oklahoma, Indiana, Michigan, Wisconsin, and West Virginia. They found that RTW laws reduce nominal wage growth by 0.6 percent roughly one year after the laws' implementation, using econometric strategies that mitigate the omitted variable problem. They further explain two indirect tests for the common theory mentioned above. First, there is a decline in the quantity of CBAs following the implementation of RTW laws, indicating that RTW laws significantly weaken unions to the extent that certain establishments opt to discontinue their union membership. In the second examination, they employ state-level data on union membership to establish that the issue of free-riding among workers intensified after the introduction of RTW laws. Both tests align with the notion that RTW laws diminish the bargaining influence of unions.[11]

Eisenach (2018) argues the opposite, stating that correlative trends are supportive of the fact that RTW laws are beneficial in terms of employment and overall personal income as businesses tend to relocate to RTW states.[12] However, multiple studies including Friedman et al. (1992)[13] and Holmes (1998) suggest otherwise. Although businesses have statistically relocated more to RTW states, it is more likely to be due to the effects of the pro-business policies of those states (see further discussion in the "RTW Laws and Employment" section), which are extremely difficult to isolate from the effects of RTW laws; thus, correlative trends are not as meaningful in this circumstance.[14]

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[9] Page, Lucy. "Impacts of Right-To-Work Laws on Unionization and Wages." NBER, 8 Aug. 2022, https://www.nber.org/digest/202208/impacts-right-work-laws-unionization-and-wages.

[10] Gould, E., & Kimball, W. (2015). "Right-to-Work" States Still Have Lower Wages. Economic Policy Institute. https://www.epi.org/publication/right-to-work-states-have-lower-wages/

[11] Chava, Sudheer, et al. "The Economic Impact of Right-To-Work Laws: Evidence from Collective Bargaining Agreements and Corporate Policies." *Journal of Financial Economics*, 8 Feb. 2020, https://doi.org/10.1016/j.jfineco.2020.02.005.

[12] Eisenach, Jeffrey. Right-To-Work Laws: The Economic Evidence. May 2018. https://www.nera.com/content/dam/nera/publications/2018/PUB_Right_to_Work_Laws_0518_web.pdf

[13] Friedman, J., Gerlowski, D. A., & Silberman, J. (1992). What Attracts Foreign Multinational Corporations? Evidence From Branch Plant Location In the United States. *Journal of Regional Science*, *32*(4), 403–418. https://doi.org/10.1111/j.1467-9787.1992.tb00197.x

[14] Holmes, Thomas J. (1998). The Effect of State Policies on the Location of Manufacturing: Evidence from State Borders. *Journal of Political Economy*, *106*(4), 667–705. https://doi.org/10.1086/250026

Nevertheless, most literature in support of RTW laws like Reed (2005)[15] and Hicks and LaFaive (2013) are based on finding a positive causal relationship between RTW laws and *average* wages. Using a statistical model and controlling for other factors, the results of their study show that from 1947 to 2011, RTW laws increased average real personal income growth by 0.8 percentage points and average annual population growth by 0.5 percent in RTW states.[16] It is of certain importance to note that these results were published by Mackinac, a right-wing economics center. Moreover, Allegretto and Lafer (2011) at the Institute for Research on Labor and Employment (IRLE) assert that data on averages presented in the absence of standard deviations tend to create the misleading impression that the average is more or less representative of everyone in the group; while, it may be that the top percentages of people have increased income, leading to a higher average.[17] This is also proven to be the actual case by Chava et al. (2020), which will be explained below.

A well-established theory about businesses, focusing on labor and capital as the main factors for production, suggests that worker wage reduction will result in increased investment, employment, profitability, and a higher ratio of labor-to-asset of a firm. Although they found no significant change in the profitability of average firms in RTW states, they found that for labor-intensive firms, those with high labor-to-asset ratios, operating profit is around 5 percent higher five years after the adoption of RTW laws. Additionally, RTW increases payout through higher dividends three years after the adoption; RTW laws have a positive effect on CEO compensation; and executives receive increases in their base salary.

Several variations of the theory proposed by Matsa (2010)[18], Michaels et al. (2019)[19], and Ellul and Pagano (2019)[20] go further to suggest that when firms have more bargaining power, it leads to a decrease in their reliance on financial leverage. These authors argue that firms use leverage as a bargaining tool during negotiations with workers. With the adoption of RTW policies, union influence decreases, weakening the need for leverage, thus expecting a decrease in leverage. Besides finding supportive results, researchers also found that firms invest more and increase employment, both of which are consistent with a drop in wages.

4.3 RTW Laws and Employment

Most research results concentrate on finding a positive or no causal relationship between RTW laws and employment. Many of the theoretical explanations also fall under two main views.

First, the business relocation theory was explained briefly in the above section on wages: RTW laws establish a business-friendly setting that grants employers greater flexibility when it comes to hiring, firing, and determining wages. This environment appeals to businesses, leading to a rise in job opportunities and employment rates within these regions. The aforementioned Holmes (1998) study finds that manufacturing

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[15] Reed, W. Robert. "How Right-To-Work Laws Affect Wages." *Ideas.repec.org*, 8 June 2005, Ideas.repec.org/p/wpa/wuwpla/0506005.html

[16] Hicks, Michael, and Michael Lafaive. Economic Growth and Right-To-Work Laws. https://www.mackinac.org/archives/2013/s2013-05.pdf

[17] What's Wrong with "Right-to-Work." (2011, February 28). Institute for Research on Labor and Employment. https://irle.berkeley.edu/publications/brief/whats-wrong-with-right-to-work-chambers-numbers-dont-add-up/

[18] Matsa, D. A. (2010). Capital Structure as a Strategic Variable: Evidence from Collective Bargaining. *The Journal of Finance*, *65*(3), 1197–1232. https://www.jstor.org/stable/25656325

[19] Michaels, R., Beau Page, T., & Whited, T. M. (2018). Labor and Capital Dynamics under Financing Frictions*. *Review of Finance*, *23*(2), 279–323. https://doi.org/10.1093/rof/rfy020

[20] Ellul, A., & Pagano, M. (2019). Corporate leverage and employees' rights in bankruptcy. *Journal of Financial Economics*, *133*(3), 685–707. https://doi.org/10.1016/j.jfineco.2019.05.002

employment in counties within 25 miles of the state borders of RTW, or "pro-business," states grew about one-third faster than counties near non-RTW, or "anti-business," states. This trend of manufacturing employment growth from 1947 to 1992 indeed proves that state policies are a major factor in influencing firm location; however, Holmes also expresses uncertainty about the isolated effects of RTW laws since his findings were based on the *overall* state policy despite using RTW laws and union security as the proxy measurement to states' business-friendliness. [21]

An additional proof is the example of North Dakota, which experienced the highest employment growth in the country from 2002 to 2012. While North Dakota is an RTW state, it also implements numerous other pro-business policies, including tax exemptions, subsidized training, and financial incentives (consistent with the aforementioned study by Holmes in 1998). Additionally, factors unrelated to policies, such as a significant abundance of natural resources, likely played a role in the employment growth observed in North Dakota during that period.

Furthermore, opponents of this theory contend that because RTW laws are established primarily in the South, which has a lower cost of living relative to the North, businesses may simply be driven by the autonomy to distribute lower wages that are caused by regional differences – not RTW laws. [22]

The second theory posits that union-exposed industries face lower labor costs along with increased profitability and thus produce higher output and employ more labor in the RTW location. The primary assumption here aligns with the results found by Chava et al. (2020) in the section on wages. Austin et al. (2020) found that using a spatial model, RTW laws increase the labor force participation rate by 1.41 percent and reduce the unemployment rate by 0.39 percent. [23]

However, Wexler (2022) argues that by looking at the controlled employment trend of RTW states after 2010, there are no significant fluctuations for both the high-union density industries and low-union density industries, while an uncontrolled regression shows a 1.6 percent reduction in employment rate across all industries. [24]

Nevertheless, it is important to note that these findings cannot simply offset one another due to differences in time span and methodology.

Table 2. *Employment levels of RTW states and union security states in 2002, 2007, and 2012 (Benjamin 2014)* [25]

	Employment (in thousands)			Change in Employment		
	2002	2007	2012	2002-2007	2007-2012	2002-2012
All States	130,245	137,390	133,724	5.5%	-2.7%	2.7%
RTW States	49,388	53,848	52,651	9.0%	-2.2%	6.6%
Union Security States	80,857	83,542	81,073	3.3%	-3.0%	0.3%

4.5 RTW Laws and Worker Well-being

[21] Holmes, Thomas J. (1998). The Effect of State Policies on the Location of Manufacturing: Evidence from State Borders. *Journal of Political Economy*, *106*(4), 667–705. https://doi.org/10.1086/250026

[22] Sherk, J. (2011, November 9). Right to Work Increases Jobs and Choices. *The Heritage Foundation*. https://www.heritage.org/jobs-and-labor/report/right-work-increases-jobs-and-choices

[23] Austin, Benjamin, et al. The Long-Run Effects of Right to Work Laws. 2021. https://scholar.harvard.edu/files/matthew-lilley/files/long-run-effects-right-to-work.pdf

[24] Wexler, N. (2022). *Wage and Employment Effects of Right-to-Work Laws in the 2010s*. https://www.aeaweb.org/conference/2023/program/paper/E8DnB4hT

[25] Collins, Benjamin. Right to Work Laws: Legislative Background and Empirical Research. 2014. https://sgp.fas.org/crs/misc/R42575.pdf

This section will analyze RTW's effects on worker well-being through two aspects: worker health and safety, both of which are shown through the outcomes of de-unionization.

Shierholz et al. (2022) found that unions improve the health and safety of workplaces by enforcing health insurance and safety protections and giving workers the confidence to negotiate with their employers without fear of retaliation. Data shows that over 90 percent of employees who are under a union agreement are provided with employer-sponsored healthcare benefits, while only 69 percent of non-union workers have the same access, as indicated by the study.[26]

Data comparing union workers and non-union workers in obtaining employer-sponsored health benefits are also relevant in the context of RTW laws; RTW laws have been shown to decrease unionization rates, establishing a triangular relationship between unions, health benefits, and RTW laws. When RTW laws diminish the bargaining power of unions or reduce the number of unions, it is likely that more workers will receive healthcare benefits similar to those of non-union workers. However, it is important to recognize that the implications of employer-sponsored health benefits extend far beyond simply paying for hospital bills. Workers who receive these health benefits are more likely to undergo regular physical examinations, increasing the chances of early detection and prevention of potential health issues.

Similar results are reported by Gould and Shierholz (2011). If the extent of benefits coverage in states without RTW laws were reduced to match the levels observed in states with such laws, approximately 2 million fewer workers would have access to health insurance, and about 3.8 million fewer workers would receive pensions across the country.[27]

Regarding workplace safety, in addition to the Bureau of Labor Statistics highlighting a correlation indicating that workplace fatalities are 54 percent higher in states with RTW laws, Zoorob's research in 2018 revealed that a 1 percent decrease in unionization resulting from RTW laws corresponds to approximately a 5 percent rise in the rate of occupational fatalities. Consequently, RTW laws have directly contributed to a 14.2 percent increase in occupational mortality by reducing unionization levels.[28]

However, Altassan et al. (2018) find conflicting data where union workers have a 51 percent higher rate of fatality when comparing nineteen different aluminum manufacturing companies. Yet, the researchers concluded that the reason for this difference remains unclear. They further propose that potential explanations such as differences in injury reporting, as union workers can report without fear of retaliation, or the effect of endogeneity, where unions typically organize workplaces that are inherently hazardous.[29]

[26] Shierholz, H., Poydock, M., Schmitt, J., & McNicholas, C. (2022, January 20). *Latest data release on unionization is a wake-up call to lawmakers: We must fix our broken system of labor law*. Economic Policy Institute.
https://www.epi.org/publication/latest-data-release-on-unionization-is-a-wake-up-call-to-lawmakers/

[27] Gould, E., & Shierholz, H. (2011). *The Compensation Penalty of "Right-to-Work" Laws*. Economic Policy Institute. https://files.epi.org/page/-/old/briefingpapers/BriefingPaper299.pdf

[28] Zoorob, Michael. *"Does "Right to Work" Imperil the Right to Health? The Effect of Labour Unions on Workplace Fatalities."* Occupational and Environmental Medicine, vol. 75, no. 10, 13 June 2018, pp. 736–738, https://doi.org/10.1136/oemed-2017-104747.

[29] Altassan, Khaled Abdulrahman, et al. "Risk of Injury by Unionization." *Journal of Occupational and Environmental Medicine, vol. 60*, no. 9, Sept. 2018, pp. 827–831, https://doi.org/10.1097/jom.0000000000001347.

5. Conclusion

5.1 Summary of Results

In the section discussing RTW laws and unionization rates, the free-rider hypothesis and the bargaining power hypothesis were introduced, both suggesting that RTW laws will reduce union power. One widely cited study found that RTW laws led to unionization rate reductions by 5-10% in the long run.[30] Furthermore, RTW laws have resulted in reduced union organizing activities and success rates. Comparative data analysis suggests that the success rates of organizing union activities fell by 46 percent and multiple different approaches all led to similar negative results.[31]

Research on the impact of RTW laws on worker wages is varied, but most studies indicate that RTW laws lead to lower wages for workers. One study found that wages in RTW states are 3.1 percent lower than in non-RTW states, resulting in $1,558 lower annual wages for a typical full-time worker.[32] Another study focused on wage growth and found that RTW laws reduce nominal wage growth by 0.6 percent. However, there are differing arguments regarding the overall economic impact of RTW laws, with some proponents claiming higher average income. Firm-level effects indicate potential benefits for labor-intensive firms, including higher operating profit (possibly due to lower labor costs) and positive effects on the wages of CEOs and managers (potentially driving up average income).[33]

Further, the RTW laws and employment sections present two main theories regarding the relationship between RTW laws and employment. The business relocation theory suggests that RTW laws create a business-friendly environment attracting employers and leading to job growth. Studies have shown that manufacturing employment in counties near RTW states grew around one-third faster than in counties near non-RTW states. However, it is challenging to isolate the specific effects of RTW laws from other pro-business policies.[34] The second theory suggests that reduced union density in RTW states leads to lower wages but increased profitability and reduced unemployment rate by 0.39 percent.[35] However, there are differing findings regarding employment trends in RTW states, with some studies showing no significant fluctuations while others suggest an increase in employment rates.[36]

Research also indicates that unions play a crucial role in improving worker health and safety. Unions enforce health insurance and safety protections, leading to better workplace conditions and increased access to employer-sponsored health benefits. More than 90 percent of workers covered by a union contract have access to these benefits compared to only 69 percent of non-union workers.[37] RTW laws, which decrease

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[30] Ellwood, David T., and Glenn Fine. "The Impact of Right-To-Work Laws on Union Organizing." *Journal of Political Economy,* vol. 95, no. 2, Apr. 1987, pp. 250–273, https://doi.org/10.1086/261454.

[31] David Ellwood and Glenn Fine, "The Impact of Right to Work Laws on Union Organizing," *Journal of Political Economy*, April 1987, pp. 250-273.

[32] Gould, Elise, and Will Kimball. "Right-To-Work" States Still Have Lower Wages." Economic Policy Institute, 2015, www.epi.org/publication/right-to-work-states-have-lower-wages/

[33] Chava, Sudheer, et al. "The Economic Impact of Right-To-Work Laws: Evidence from Collective Bargaining Agreements and Corporate Policies." *Journal of Financial Economics*, 8 Feb. 2020, https://doi.org/10.1016/j.jfineco.2020.02.005

[34] Holmes, Thomas J. (1998). The Effect of State Policies on the Location of Manufacturing: Evidence from State Borders. Journal of Political Economy, 106(4), 667–705. https://doi.org/10.1086/250026

[35] Austin, Benjamin, et al. The Long-Run Effects of Right to Work Laws. 2021. https://scholar.harvard.edu/files/matthew-lilley/files/long-run-effects-right-to-work.pdf

[36] Wexler, N. (2022). *Wage and Employment Effects of Right-to-Work Laws in the 2010s.* https://www.aeaweb.org/conference/2023/program/paper/E8DnB4hT

[37] Shierholz, Heidi, et al. "Latest Data Release on Unionization Is a Wake-up Call to Lawmakers: We Must Fix Our Broken System of Labor Law." Economic Policy Institute, 20 Jan. 2022, www.epi.org/publication/latest-data-release-on-unionization-is-a-wake-up-call-to-lawmakers/.

unionization rates, can have negative implications for worker wellbeing. Studies have shown that RTW laws are associated with a decrease in unionization, resulting in fewer workers receiving health insurance and pensions.[38] Additionally, workplace fatalities and occupational mortality rates tend to be higher in RTW states, with a 1 percent decline in unionization due to RTW corresponding to a 5 percent increase in the rate of occupational fatalities.[39] However, there are conflicting findings regarding the correlation between unions and workplace safety, and further research is needed to understand the underlying factors contributing to these differences.

5.2 Potential Limitations

It is difficult to completely isolate the effect of RTW laws from other variables like labor force characteristics, local policies, worker traits, etc. In an attempt to estimate the impact of RTW laws, researchers have employed various techniques while accounting for other factors in dynamic and complex economies. It is expected that different methodologies would lead to diverse conclusions. Although this paper is not exhaustive, it aims to include frequently referenced studies and research that specifically focus on isolating the effects of RTW laws on different outcomes.

5.3 Future Recommended Research Areas

One important area for future research lies in conducting regional and industry-specific analyses. Labor market characteristics and economic conditions can vary significantly across regions, and different industries may also respond differently to RTW laws. By exploring the regional and industry-specific variations in the impact of these laws, researchers can gain a more nuanced understanding of their effects. This analysis can help identify factors that influence the outcomes, contributing to a more comprehensive understanding of how RTW laws interact with different contexts.

Furthermore, conducting comparative studies across states or countries with varying RTW laws can offer valuable insights into cross-regional differences and the influence of contextual factors. Comparing regions with different policy environments allows researchers to isolate the specific effects of RTW laws and provide a broader perspective on their implications. Such comparative research can reveal the different outcomes associated with varying policy approaches and provide valuable lessons for policymakers.

Additionally, exploring the heterogeneous impacts of RTW laws across different demographic groups can provide valuable insights into the distributional consequences. Researchers can analyze how these laws affect wages and employment for different age cohorts, education levels, and racial or ethnic backgrounds. Understanding how RTW laws interact with various segments of the workforce can help identify potential equity considerations and inform policy discussions aimed at reducing disparities.

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[38] "Right-To-Work 101." Center for American Progress Action, www.americanprogressaction.org/article/right-to-work-101/.

[39] Zoorob, Michael. "Does "Right to Work" Imperil the Right to Health? The Effect of Labour Unions on Workplace Fatalities." *Occupational and Environmental Medicine, vol. 75,* no. 10, 13 June 2018, pp. 736–738, https://doi.org/10.1136/oemed-2017-104747.

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