DISSERTATION

FASHION THINKING: 3D SIMULATION SOFTWARE, COGNITION, AND CRITICAL THINKING

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ABSTRACT

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This dissertation comprises three articles that collectively explore the cognitive and critical thinking processes involved in fashion design within virtual environments, with a particular focus on 3D simulation software. The first article establishes the theoretical foundation by introducing the THREAD framework, which highlights the integration of critical thinking and design cognition, emphasizing the hybrid nature of digital and physical workflows. THREAD identifies seven key tenets of design cognition and critical thinking: problem-solving, reflexivity, individual agency, tacit knowledge, spatial visualization, haptic memory, and creativity.

The second article presents an empirical study investigating how undergraduate fashion design students engage in critical thinking while using 3D simulation software utilizing think aloud protocol methodology. Findings reveal that students exhibit reflexivity, creativity, and independent decision-making but often struggle to balance digital autonomy with deeper design analysis. The flexibility of CLO 3D fosters risk-taking yet sometimes leads to reactive rather than strategic choices. The third article examines the cognitive processes of fashion designers working in virtual environments through semi-structured artifact interviews. Key insights include the role of tacit knowledge in developing design intuition, the enhancement of spatial visualization through real-time adjustments, the engagement of haptic memory despite the absence of physical touch, and the impact of digital tools on creativity and exploration. Notably, gamification within CLO 3D encourages experimentation and risk-taking but necessitates structured reflection to maintain design depth. Synthesizing these findings, the dissertation identifies three overarching insights. First, 3D fashion thinking is inherently hybrid, blending physical and digital processes. Second, designers must develop novel cognitive strategies to adapt to digital materiality. Third, gamification is reshaping creativity within virtual design environments.

Through this research, the original THREAD framework has been revised to incorporate new dimensions of virtual fashion thinking. The concept of haptic memory has been expanded to include material perception, recognizing the cognitive strategies designers employ to assess digital representations of materials. Creativity is now understood as inherently linked to playful exploration, emphasizing the role of gamified experimentation in fostering design innovation. Emotional and motivational engagement has been introduced as a crucial factor, highlighting the psychological dimensions that sustain creative momentum in virtual design. Reflexivity has been refined into two distinct levels: reactive reflexivity, which involves immediate, real-time adjustments, and strategic reflexivity, which encompasses deeper, conceptual design analysis. Additionally, perceptual adaptation has been identified as a key cognitive shift required when transitioning from physical to virtual workflows, addressing the need for designers to interpret digital materials without tactile feedback. The research contributes to the evolving discourse on virtual fashion education and practice, offering insights into how designers navigate and innovate within emerging digital spaces.

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CHAPTER 1: INTRODUCTION

This work is divided into three articles that explore different aspects of fashion thinking when utilizing 3D simulation software as a design tool, allowing for a comprehensive and focused exploration. The three articles comprising this work (1) develop a framework, THREAD, for understanding fashion thinking within the context of virtual fashion design pedagogy, (2) explore 3D simulation software as a tool for critical thinking skills among student designers, utilizing a novel framework, THREAD, and (3) analyze, archive, and elucidate the cognition involved when creating in the virtual environment, to formally capture the knowledge of the field of fashion design as cognitive praxis. This approach creates space for the development and application of the framework in addition to more in-depth exploration and examination of the specific areas of critical thinking and design cognition, informing and elucidating fashion thinking. By addressing different facets of 3D fashion thinking from various angles, the result will strive to be comprehensive and holistic, laying the groundwork for future research. Each study serves as a vital piece of a larger puzzle, contributing to the knowledge base of the cognitive processes inherent in virtual fashion design.

Research Motivation

This 3-part study is prompted by a historical lack of scholarly inquiry into the cognitive aspects of fashion design (Gully, 2010) and concerns about the adequacy of critical thinking skills among graduating student designers (Fiore et al., 2005). Fashion design has often been marginalized in discussions surrounding design cognition, with little critical examination of its unique attributes compared to other design subfields (Nixon & Blakley, 2012). Despite the growth of the larger design profession, fashion design has been overlooked, and research into its actual design processes remains limited (Chun, 2018), as the academic discussion in fashion typically centers on the designed objects, not the design of objects (Chun, 2018). This 3-part dissertation exploring fashion thinking is situated within the virtual environment because fashion thinking "adds value to the functional and experiential spheres of products" (Nixon & Blakley, 2012, p. 153). By exploring fashion thinking within the virtual environment, perhaps we can better understand how technology influences the creative and critical processes in the practice of fashion design.

The growing integration of 3D simulation software in fashion education presents an opportunity to address the aforementioned deficiencies as it is shown to improve critical thinking in other disciplines (Suryanti et al., 2020; Syawaludin et al., 2019; Tercete et al., 2017; Astuti et al., 2020), yet evidence of how this software engages critical cognition in fashion design students remains lacking (Han, 2010). As the fashion industry enters its fourth industrial revolution, the widespread adoption of 3D simulation software in undergraduate fashion programs has become increasingly common (Kunz & Rupe, 1999), underscoring the need to remedy the gap in understanding fashion thinking within the virtual environment (Ernawati et al., 2022). This novel integration of virtual learning in fashion academia is driven by the industry's need for more efficient design and fitting processes, as traditional methods are often cost-prohibitive and time-consuming (Kunz & Rupe, 1999). As such, the newfound efficiencies of 3D design have led to a shortage of designers with the necessary cognitive skills to utilize this technology effectively (Grain, 2021). Digital literacy, which has been found to necessitate critical thinking skills (Amin et al., 2023), has been cited as a key area of deficiency it is necessary in order to utilize design software effectively (Ernawati et al., 2022; Avila & Pandya, 2013). These factors collectively underscore the need for an exploration of fashion thinking in the context of virtual design environments from a few different angles.

The emergent framework, THREAD, which is introduced and developed in Paper 1, will provide a scaffold for understanding fashion thinking within the context of virtual fashion design pedagogy. Additionally, exploring 3D simulation software as a tool for critical thinking skills among student designers and analyzing the cognition involved in creating in the virtual environment will shed light on the cognitive processes specific to the virtual space. Ultimately, this research will contribute to improving fashion design education and professional practice by contributing to the formalization of the knowledge of the field by elucidating the cognitive and critical components of fashion thinking in 3D.

Researcher Perspective

As a 3D Design Manager at a Fortune 500 outdoor fashion company and an adjunct instructor of fashion design at a western arts college, my professional journey has been deeply intertwined with both industry innovation and fashion education. My expertise lies in digital and virtual design, where I have spent the past seven years teaching undergraduate fashion design students, developing curriculum, and authoring coursework on 3D simulation software and CAD for fashion design. These experiences have provided me with a unique vantage point to observe the evolution of fashion education and the increasing role of technology in shaping creative and critical thinking skills among emerging designers.

My motivation for this study comes from my own experiences as both an educator and a professional working at the intersection of fashion and technology. Throughout my career, I have witnessed how fashion design is often treated as purely aesthetic or intuitive, rather than being recognized as a discipline requiring complex problem-solving, spatial reasoning, and critical thinking. While teaching, I have seen many talented students struggle—not because they lack creativity, but because they lack the structured cognitive tools needed to translate their ideas into functional, innovative designs. At the same time, I've seen how technology, particularly 3D simulation software, is reshaping the way designers work. In industry, the shift toward digital workflows is happening rapidly, and yet many graduating students are unprepared for these new demands. There is a disconnect between the way fashion design has traditionally been taught and the evolving skills the industry now requires. I have spent years developing curriculum to bridge this gap, but I've found that simply teaching software isn't enough—what truly matters is understanding how designers think in these digital environments.

This study addresses an area that has long been overlooked: the cognitive process behind fashion design. I want to understand how designers develop ideas, solve problems, and make creative decisions in virtual spaces. By shedding light on the thinking behind the design process, I hope to help both educators and students navigate this technological shift with a stronger foundation, ensuring that the next generation of designers is equipped not just with technical skills, but with the critical thinking abilities needed to push the field forward.

Industry 4.0

Given that critical thinking is a fundamental skill for success in the modern workforce, particularly in creative fields like fashion design, evaluating the effectiveness of 3D simulation software in enhancing this skill is essential for preparing students for the demands of the industry (Benešová & Tupa, 2017; Cabrita et al., 2020). In the era of Industry 4.0, where automation, artificial intelligence, and data analytics are revolutionizing traditional manufacturing and design processes, student designers must possess not only technical skills but also critical thinking abilities to adapt to these changes (Rübmann et al., 2015). The advancements in Industry 4.0 technologies have compelled fashion companies to seek designers proficient in virtual production and design tools, creating a demand for a new skillset in the industry (Sun & Zhao, 2018; McQuillan, 2020). One of the key emerging tools of Industry 4.0, 3D simulation software offers a platform for students to engage in complex design tasks, problem-solving challenges, and iterative processes, all of which are integral to developing critical thinking skills (Thomke & Fujimoto, 2000). By investigating how effectively 3D simulation software cultivates critical thinking among student fashion designers, educators and industry professionals can better understand its potential to prepare future designers for the evolving demands of the fashion industry in the digital age.

Educational Implications

Additionally, exploring critical thinking as it is situated in the virtual design environment can inform pedagogical practices in fashion design education. As educators seek innovative ways to enhance student learning experiences and outcomes, evidence-based research on digital tools like 3D simulation software can guide curriculum development, instructional strategies, and assessment methods. It is essential to expand our understanding of fashion thinking, especially as the industry transforms to the novel environment of contemporary technology, characterized by smart digital and virtual design tools and decentralized systems (Bertola & Teunissen, 2018). And, it is known that technology adaptation sets frames for and drives designers' creative outputs (Genova & Moriwaki, 2016; Bertola & Teunissen, 2018). Technology use has been cited as a key component of the exercise of fashion thinking as it, "adds value to the functional and experiential spheres of products"" (Nixon & Blakely, 2012, p. 153). As such, by identifying best practices and areas for improvement, educators can optimize the integration of 3D simulation software into fashion design programs, ultimately better preparing students for successful careers in the dynamic and increasingly technology-driven fashion industry.

Fashion Thinking

There are a few different ways that fashion thinking has been conceptualized, and some researchers have argued that the concept of fashion thinking, due to its novelty, is not yet stabilized (Petersen et al., 2016; Chun, 2019). Fashion thinking is often described as an epistemology and a methodology in and of itself, where it is a tool to create visual and material representations of time and place (Nixon & Blakely, 2012; Aspers & Godart, 2013; Pecorari, 2016; Buckley & Clark, 2018). It has been noted that fashion thinking can be understood through Cross's (2006) emphasis on 'designerly ways of knowing' (Mazzarella et al., 2019), where designers translate meaning through hands-on experience with materials and objects.

One of the most widely accepted understandings of fashion thinking is that it is something of a framework of critical thought and problem-solving applied to the design and development of fashion product (Dieffenbacher, 2021). Fashion thinking has been defined as, "a paradigm of critical thought and creative agency utilizing technology, story, experimentation, and open sourcing in order to add meaning and value to the functional and experiential spheres of products and services" (Nixon & Blakely, 2012, p. 157). Centering on 4 key features, fashion thinking refers to the "engagement with temporal, spatial, and socially discursive dimensions, as well as the priority placed on the articulation of taste and balancing commercial goals with artistic innovation" (Nixon & Blakely, 2012, p. 157). In this conceptualization, fashion thinking has been described as a paradigm comprised of five distinct features including: 1) temporal, 2) spatial, 3) social, 4) aesthetic, and 5) the balance of commercial goals with artistic innovation (Nixon & Blakely, 2012). These 5 features of fashion thinking can be categorized as either critical thinking or design cognition, underscoring the need for an intimate understanding of both. A methodological knowledge, design thinking has been cited as one of the greatest sources of inspiration and influence on the concept of fashion thinking (Nixon & Blakely, 2012). Design thinking can be understood as a cognitive style characterized by reasoning and problem-solving; symbolizing the reconceptualization of design from creating physical products to solving complex issues and exercising cognitive processes and methods to do so (Petersen et al., 2016). The transformation of design from confinement within the traditional activity of “making” and giving shape and form to physical objects to the conceptualization of design as an iterative cognitive process and a field of innovation (Petersen et al., 2016), is mirrored in the fashion specialization of design.

Fashion thinking is the act of producing analytical thoughts; it is a “strategy of analysis, as a specific way of thinking through functional and experiential spheres of the fashion design arena” (Petersen et al., 2016, p. 5). Fashion thinking encompasses both design cognition and critical thinking as separate, yet intimately connected parts to a whole. Petersen, Mackinney-Valentin, and Riegels Melchior have centered fashion thinking on the overarching objective of critical thought stimulation (2016). Design cognition plays a pivotal role in fashion thinking by facilitating the cognitive processes involved in the creation and interpretation of three-dimensional fashion artifacts (Swindells & Almond, 2016). In, "Reflections on Sculptural Thinking in Fashion," Swindells and Almond delve into theories, concepts, and philosophies related to thought and the experience of crafting three-dimensional fashion pieces, drawing parallels between sculpture and fashion, highlighting shared elements such as the sense of touch, mimicry, and empathy (2016). As such, studying both critical thinking and design cognition is essential for a holistic understanding of fashion thinking, as they collectively inform the analytical and creative processes integral to fashion design practice.

Critical Thinking and Design Cognition

Together, critical thinking and design cognition form complementary aspects of fashion thinking, each contributing unique perspectives and skills to the design process. Critical thinking provides a framework for evaluating and refining design ideas, ensuring that they meet functional, aesthetic, and ethical criteria (Nixon & Blakely, 2012). Design cognition, on the other hand, fuels the creative exploration and experimentation essential for pushing the boundaries of fashion design through the senses of touch, mimicry, and empathy (Swindells & Almond, 2016).

In the realm of fashion, critical thinking and design cognition serve as complementary yet distinct elements, each playing a vital role in the creative process. Design cognition, rooted in the intuitive and creative realm of the right brain (Cross, 2006), embodies the intuitive knowing, tactile exploration, and tacit aesthetic sense that designers employ to conceptualize and refine their creations. This intuitive knowing allows designers to tap into their innate creativity, relying on intuition and empathy to guide them through the process of envisioning innovative concepts and exploring unconventional ideas (Treadaway, 2007). Thinking through the hands, designers engage in hands-on experimentation, manipulating fabrics, patterns, and textures to bring their creative visions to life (Sun, 2015). This tactile thinking enables them to explore different possibilities and refine designs through direct interaction with materials. Additionally, designers develop a tacit aesthetic sense through exposure to various design influences and experiences, enabling them to make instinctual decisions about color palettes, proportions, and stylistic elements, thus contributing to the overall visual appeal of their creations.

On the other hand, critical thinking, associated with the analytical and problem-solving capabilities of the left brain, plays a crucial role in identifying and addressing challenges throughout the design process (de Wet, 2015). Designers employ critical thinking to analyze issues such as technical constraints, budget limitations, or market demands, and develop strategic solutions to overcome them effectively (Butler-Young, 2022). This involves constant searching for innovative solutions to design problems, drawing on analytical skills to evaluate different approaches and determine the most viable options. Critical thinking in fashion also entails assessing the feasibility of ideas, conducting market research, and identifying opportunities for improvement. Through this analytical process, designers refine their designs to ensure they meet the desired objectives and resonate with the target audience.

Conceptualizing with the right brain/left brain analogy (Figure 1.1), design cognition represents the intuitive, imaginative, and creative aspects of fashion thinking, akin to the artistic side of the brain. In contrast, critical thinking corresponds to the analytical, logical, and problem-solving aspects, akin to the strategic side of the brain. Together, design cognition and critical thinking form a balanced approach to fashion thinking, blending artistic vision with strategic thinking to produce innovative and successful creations. By harnessing the strengths of both aspects of fashion thinking, designers can navigate the complexities of the fashion industry, transforming abstract ideas into tangible expressions of style and creativity.

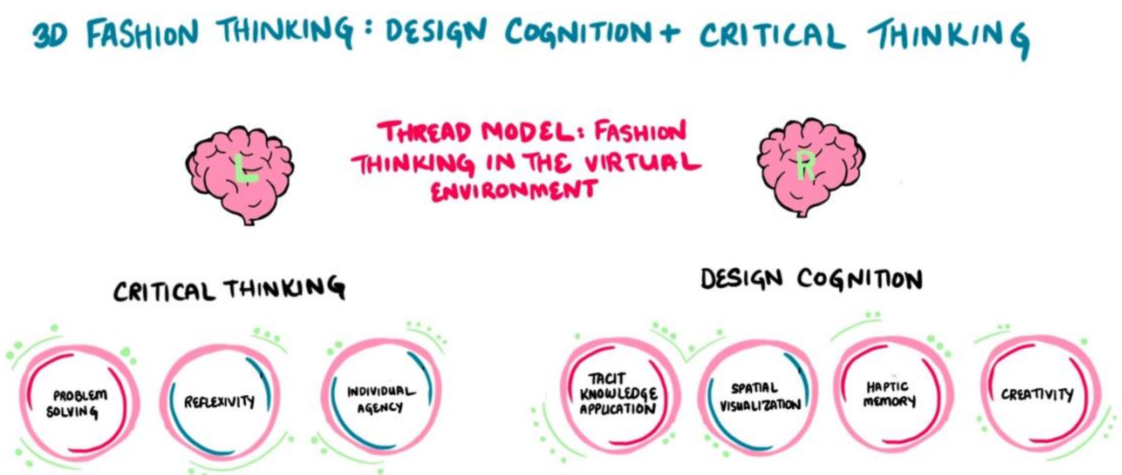

Figure 1.1

Critical Thinking

Critical thinking is inherently present as a tenet of fashion thinking, as fashion thinking necessitates critical thought (Postlethwaite, 2022). According to Vänskä (2018), fashion thinking is a, “form of knowledge production” that provides the tools for critical thinking (p. 18). Critical thinking primarily involves the analytical and evaluative processes used to assess information, identify problems, and generate solutions (de Wet, 2015). Critical thinking for fashion design involves the systematic evaluation and refinement of design ideas across three fundamental planning stages, as outlined by de Wet (2015). Firstly, the exploration and collection of diverse concepts during the divergent design phase; secondly, the critical selection and elimination of ideas based on predetermined criteria; and finally, the synthesis and arrangement of chosen ideas using design principles to create cohesive and innovative design solutions (de Wet, 2015). As such, critical thinking in design revolves around strategic decision-making and creative problem-solving.

The fashion designer of the fourth industrial revolution, often referred to as Fashion Designer 4.0 and digital artisan (Särmäkari, 2022), requires a blend of traditional fashion knowledge and advanced digital skills, along with qualities such as data literacy, flexibility, analytical readiness, and, especially, critical thinking (Butler-Young, 2022). Critical thinking skills and social interoperability have become increasingly vital, whether working independently within a global network or collaborating within multidisciplinary teams (Butler-Young, 2022). However, despite the growing demand for digital expertise in the fashion industry, the digitalization of fashion design remains understudied academically, presenting numerous avenues for exploration, particularly in learning and education (Butler-Young, 2022). As fashion companies increasingly seek talent in 3D design, there is a growing recognition of virtual fashion design skills for the fashion designer 4.0 (Butler-Young, 2022).

Design Cognition

On the other hand, design cognition delves into the underlying cognitive processes and mental models that shape designers' creative thinking, encompassing the intuitive understanding of design principles, the iterative process of ideation and iteration, and the application of tacit knowledge acquired through experience and practice (Hay et al., 2020). Design cognition refers to the cognitive processes involved in creative tasks within the realm of design (Hay et al., 2020). Drawing from cognitive science, design cognition encompasses the dual-process models of creativity, which highlight the interplay between spontaneous, unconscious retrieval and association of representations from memory, and more deliberate, conscious evaluation and modification of ideas to align with task objectives and limitations (Beaty, et al., 2018). This suggests that design cognition involves a complex interplay between memory processes and creativity, ultimately shaping the way designers conceptualize, develop, and refine their ideas to meet design goals.

Situated within the 3D context, design cognition as it exists within the realm of fashion thinking, encompasses the intricate interplay between human agency, thinking, and embodiment, which are seamlessly extended and augmented by digital technologies (Hayles, 2012; Lupton, 2017). In this context of technogenesis, where humans co-evolve with technology, designers engage in a symbiotic relationship with 3D simulation software, with the software becoming an extension of their bodies and cognitive processes (Hayles, 2017). Through this interaction, designers not only learn from the software but also shape it through their embodied experiences, resulting in a dynamic human-computer-designer hybrid where bodily knowledge is translated into digital form (Särmäkari & Vänskä, 2021; Särmäkari, 2021).

Fashion thinking in the virtual environment encompasses both critical thinking and design cognition, with critical thinking providing the analytical framework for evaluating and refining design ideas, while design cognition fuels creative exploration and experimentation (Nixon & Blakely, 2012; Swindells & Almond, 2016). Investigating these components separately is necessary to fully understand fashion thinking in the 3D environment, as critical thinking involves strategic decision-making and problem-solving, while design cognition delves into the underlying cognitive processes shaping designers' creative thinking (Beaty et al., 2018; Hay et al., 2020).

Three Article Structure

The structure of this 3-article work is comprised of a theoretical article which develops and proposes a framework derived from a meta-narrative literature review, in addition to two empirical studies. The two empirical studies look at the two different angles of fashion thinking, creating space for the exploration of critical thinking and design cognition separately, tailoring methodologies and data analysis approaches to each aspect. This approach enhances the rigor and depth of the research, providing valuable insights into the multifaceted nature of fashion thinking and the intersection of 3D simulation software and designers' cognitive processes. The framework of fashion thinking developed in the theoretical article, the THREAD model, addresses both critical thinking and design cognition in two different studies by incorporating specific methodologies and research approaches tailored to each area of inquiry.

Paper 1

The first paper, which is a conceptual endeavor entitled, Fashion Thinking in the virtual environment: Towards a Novel Disciplinary Framework for Pedagogical Design, the foundational groundwork is laid for the subsequent investigations by developing a robust framework for comprehending fashion thinking and generalized design cognition within the unique context of virtual fashion design pedagogy. This endeavor stems from a recognition of the glaring gap in the existing literature, which fails to provide a structured framework for grasping the implicit cognitive and critical mechanisms at play in the utilization of 3D simulation software within undergraduate fashion design education. By meticulously crafting a framework through a meta-narrative literature review, entitled THREAD, this study endeavors to establish a theoretical scaffold upon which subsequent research endeavors can build. This first paper offers a systematic lens through which to analyze and interpret the complexities of critical thinking and design cognition when utilizing 3D simulation software in fashion design pedagogy.

The THREAD framework introduces seven key tenets that encompass both design cognition and critical thinking in fashion thinking. Design cognition focuses on intuitive and creative aspects, including tacit knowledge, spatial visualization, haptic memory, and creativity. Designers rely on their intuitive understanding, spatial visualization skills, sensory experiences, and creativity to envision and refine designs effectively. Critical thinking involves problem-solving, reflexivity, and individual agency. Designers analyze challenges, reflect on biases and assumptions, and exercise deliberate choices to drive innovation in the fashion industry. By integrating these elements, the THREAD framework provides a balanced approach to fashion thinking, combining artistic vision with strategic analysis to produce innovative designs.

Paper 2

Paper 2 is an empirical work entitled, Fashion Thinking in Industry 4.0: 3D Simulation Software and Critical Thinking. This paper shifts the focus from theoretical development to empirical assessment, aiming to evaluate 3D simulation software on the development of critical thinking skills among undergraduate fashion design students. This shift is motivated by a recognition of the pressing need to bridge the gap between theoretical frameworks and real-world applications. This study is contextualized within Industry 4.0, where the integration of digital technologies is reshaping the landscape of fashion production and design. By employing the three tenets relevant to critical thinking from the theoretical framework established in Paper 1, this study seeks to shed empirical light on the efficacy of 3D simulation software as a tool for fostering critical thinking, as a subset of fashion thinking, thereby addressing a critical gap in the literature, and offering valuable insights for both academic and industrial stakeholders.

Paper 2 seeks to answer the research question: How does the virtual environment produced by 3D simulation software engage critical thinking skills in the fashion design process? To investigate this question, the study employs the think-aloud protocol, a method designed to capture participants' cognitive processes in real-time. Through screen recordings and verbal narration, participants are observed as they develop their capsule collection project in 3D CLO software. The think-aloud protocol offers a valuable opportunity to observe participants' critical cognition as it unfolds, providing real-time insights into the ways in which the virtual environment engages the critical thinking skills innate to fashion thinking. By recording students' screens and voices during the design process, researchers can gain a nuanced understanding of the immediate critical responses elicited by 3D simulation software.

Paper 3

Paper 3 is entitled, Decoding the Abstract: 3D Simulation Software and Fashion Design Cognition. This work delves into the intricate nuances of fashion design cognition in the virtual environment, aiming to decode the abstract processes underlying the utilization of 3D simulation software in fashion design thinking and learning. Building upon the theoretical foundation laid in Paper 1, this study seeks to unravel the tacit complexities of fashion design cognition and formally capture the knowledge embedded within the praxis of virtual fashion design. By leveraging the relevant 4 tenets of the THREAD framework developed in Paper 1, this study endeavors to provide an analysis of the cognitive processes involved in creating within the virtual environment, offering insights for advancing our understanding of fashion thinking in the digital age.

Paper 3 aims to address the research question: What are the specific cognitive processes and strategies utilized by fashion designers when creating within the virtual environment, and how do these processes contribute to the formalization and capture of knowledge within the field of fashion design as cognitive praxis? To explore this question, the study utilizes semi-structured artifact interviews, allowing for in-depth exploration of participants' cognition when designing in 3D simulation software. The interviews will provide a platform for reflective dialogue and introspection (van Manen, 1990). By engaging participants in conversations about their design processes and decision-making strategies, researchers can uncover underlying cognitive mechanisms that may not be readily apparent through real-time observation alone. Additionally, the digital nature of the interviews allows for the sharing of design processes through screen-sharing and sketching, further enhancing participants' ability to articulate their cognitive strategies and reflect critically on their design practices (Van Zeeland et al., 2021; Bryman, 2016; Lo Iacono et al., 2016).

Dissertation Roadmap

This dissertation is structured as a three-article study that examines fashion thinking within virtual environments (Table 1.1). Through a combination of theoretical development and empirical investigation, this work seeks to establish a comprehensive understanding of the cognitive processes involved in fashion design when utilizing 3D simulation software. The first paper develops the THREAD framework, a structured approach to fashion thinking based on a meta-narrative literature review. THREAD identifies seven tenets—four related to design cognition (tacit knowledge, spatial visualization, haptic memory, and creativity) and three to critical thinking (problem-solving, reflexivity, and individual agency). This theoretical foundation guides the empirical studies as both a conceptual tool and analytical framework. Papers 2 and 3 function as interconnected empirical studies that apply the THREAD framework to explore two dimensions of fashion thinking: critical thinking and design cognition. These papers are best understood as two complementary parts of a single study, with each focusing on a distinct yet interrelated aspect of cognitive engagement in virtual fashion design environments.

Following the empirical investigations in Papers 2 and 3, Chapter 5 revisits the THREAD framework in light of the two studys' findings. By integrating insights from both empirical studies, this chapter refines the conceptual model and evaluates its effectiveness in capturing the cognitive complexities of fashion thinking. Additionally, Chapter 5 emphasizes the practical implications of this research for fashion design education. Given the increasing adoption of 3D simulation software in undergraduate curricula and industry settings, these findings provide valuable guidance for educators seeking to enhance critical thinking and cognitive engagement in virtual design pedagogy. By developing and empirically testing the THREAD framework, this study not only advances theoretical discourse but also offers practical strategies for strengthening virtual literacy, critical thinking, and design cognition in emerging fashion professionals. The richness of this research lies in its ability to bridge theoretical insights with applied practice, ultimately shaping the future of fashion design education and digital innovation.

Table 1.1

Dissertation Roadmap

Dissertation Chapter	Title/Focus	Description
Ch. 1	Justification and Structure	Provides the overarching justification for this three-part dissertation. Introduces the critical thinking/design cognition duality within 3D fashion thinking, framing the need for a structured investigation into the cognitive aspects of virtual design. Explains the three-article structure and how each study contributes to understanding 3D fashion thinking.
Ch. 2 (Paper 1)	Fashion Thinking in the Virtual Environment: Towards a Novel Disciplinary Framework for Pedagogical Design	Develops the THREAD framework through a meta-narrative literature review. Identifies seven key tenets—four related to design cognition (tacit knowledge, spatial visualization, haptic memory, and creativity) and three to critical thinking (problem-solving, reflexivity, and individual agency). Establishes a theoretical foundation for the empirical studies.
Ch. 3 (Paper 2)	Fashion Thinking in Industry 4.0: 3D Simulation Software and Critical Thinking	Empirical study examining how 3D simulation software influences critical thinking in fashion design students. Applies the critical thinking tenets of THREAD and uses think-aloud protocols to capture students' real-time engagement.
Ch. 4 (Paper 3)	Decoding the Abstract: 3D Simulation Software and Fashion Design Cognition	Empirical study exploring the cognitive processes involved in virtual fashion design. Uses the design cognition tenets of THREAD and artifact-based interviews to analyze students' intuitive and creative decision-making within 3D software.
Ch. 5	Refining THREAD and Practical Implications	Revisits the THREAD framework in light of the empirical studies' findings. Refines the model and evaluates its effectiveness in capturing the cognitive complexities of 3D fashion thinking. Discusses practical implications for fashion design education and provides guidance for educators on enhancing critical thinking and cognitive engagement in virtual design pedagogy.

Conclusion

This collection of three articles represents an endeavor to unravel the complexities of fashion thinking in the realm of virtual design. By developing a novel disciplinary framework of fashion thinking situated within 3D simulation software, and dissecting the cognitive processes underlying virtual design, these studies collectively contribute to a comprehensive understanding of fashion thinking in the digital age.

The theoretical groundwork laid in the first paper lays the foundation for subsequent investigations by proposing a robust framework for comprehending fashion thinking, as it is comprised of critical thinking and design cognition, within the virtual environment. This foundational work not only addresses the existing gap in the literature but also provides a systematic lens through which to analyze the complexities of critical thinking and design cognition in the context of fashion thinking for 3D simulation software.

The empirical investigations aim to provide a nuanced understanding of the fashion thinking involved in virtual design, shedding light on critical thinking and design cognition within the digital landscape. By employing methodologies tailored to each aspect of fashion thinking, the studies offer valuable insights into the multifaceted nature of design cognition and critical thinking, informing pedagogical practices, design processes, and future research directions.

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CHAPTER 2

PAPER 1: FASHION THINKING IN THE VIRTUAL ENVIRONMENT: TOWARDS A NOVEL DISCIPLINARY FRAMEWORK FOR PEDAGOGICAL DESIGN

Overview

A meta-narrative literature review of knowledge in parallel disciplines identified the paucity of an existing framework of thinking in the context of pedagogy that is applicable to the fashion design discipline, or more precisely, 3D fashion design. This theoretical article assesses and analyzes a broad literary landscape, resulting in an emergent framework, THREAD. It proposes and outlines seven overarching tenets permeating the literature review and analysis that link to both critical thinking and design cognition, as separate yet intertwined elements of fashion thinking. The seven tenets including Creativity, Tacit Knowledge, Reflexivity, Visualization, Problem Solving, Individual Agency, and Haptic Memory, are classified in relation to their capacity to develop fashion thinking in the virtual fashion design learning environment. Design cognition focuses on intuitive and creative aspects, including tacit knowledge, spatial visualization, haptic memory, and creativity. Critical thinking involves problem-solving, reflexivity, and individual agency. The work also proposes and discusses the circumstances in which the framework might be adopted and explored, as well the potential implications and future recommended research pertaining to the study outcome.

Introduction

The "THREAD" theoretical framework presented in this meta-narrative conceptual paper metaphorically represents the interconnectedness and continuity of cognitive processes in the 3D fashion design learning environment. Each tenet of the THREAD model—Creativity, Tacit Knowledge, Reflexivity, Spatial Visualization, Problem Solving, Individual Agency, and

Haptic Memory—threads through a designer's mind, symbolizing different aspects of fashion thinking. The entire fashion design discipline remains largely under-studied and unrecognized as a learned, critical, and cognitive practice, particularly within the context of virtual spaces (Chun, 2018). This oversight can be attributed to the tacit nature of the design process, common across many art and design disciplines (Gully, 2010). Fashion design has often been marginalized in discussions of design cognition, with limited examination of its unique attributes compared to other design subfields (Nixon & Blakley, 2012; Chun, 2018).

The integration of 3D simulation software in fashion education presents an opportunity to address these deficiencies, highlighting how technology influences creative and critical processes in fashion design (Nixon & Blakley, 2012). This novel virtual design environment is driven by the industry's need for more efficient design processes, leading to a shortage of designers equipped with the cognitive skills necessary to utilize this technology effectively (Kunz & Rupe, 1999; Grain, 2021). A framework derived from a meta-narrative literature review aims to elucidate fashion thinking within the virtual environment as it pertains to fashion design pedagogy. This conceptual framework provides student designers, professional designers, and researchers with insights into the innate maker methodology in the virtual environment, offering a unique opportunity to enhance the fashion design discipline.

Purpose

The shift to critical thought and creative agency in fashion adds value to the apparel industry (Petersen et al., 2016) and requires innovative pedagogical approaches. The THREAD model, derived from a meta-narrative literature review, serves as both a data analysis tool and a conceptual framework for understanding fashion thinking in virtual environments. It emphasizes seven tenets—Problem Solving, Reflexivity, Individual Agency, Tacit Knowledge Application, Spatial Visualization, Haptic Memory, and Creativity. These tenets help researchers and practitioners analyze the cognitive and creative processes in 3D fashion design, identifying areas for improvement and innovation.

THREAD bridges analytical skills and experiential knowledge, crucial for designers operating in virtual spaces, where the interplay of visual, tactile, and spatial elements is complex and multifaceted (Wann & Mon-Williams, 1996). It can be used to map out specific cognitive and creative actions in real-time, providing insights into virtual fashion design dynamics. This analysis can inform the development of educational tools, design software, and collaborative practices, enhancing designers' effectiveness and creativity in digital settings. In summary, this work presents a meta-narrative literature review and develops a framework for understanding critical thinking and design cognition within the larger category of fashion thinking, in fashion design pedagogy.

Justification

Fashion studies, while gaining traction as an interdisciplinary field, still necessitates a stronger foundation (Smal & Lavelle, 2011). The fragmented landscape of fashion studies, with contributions from various disciplines, calls for fresh perspectives to conceptualize fashion's dynamic nature (Riello & McNeil, 2010; Smelik, 2018). Technological advancements further alter the way fashion design is conducted as praxis, highlighting the need to address conceptual challenges in understanding fashion's theoretical dimension (Smelik, 2018). A meta-narrative literature review is essential for assessing the literary landscape and developing integrative theories in fashion design (McNeil, 2010; Davis, 2008). Despite calls for such frameworks, gaps remain in understanding the cognitive mechanisms underlying fashion design practices, especially in virtual environments (Jenss, 2016). This study introduces a framework that consolidates existing knowledge, bridges disciplinary gaps, and provides a structured approach to advance fashion studies.

Duality of Fashion Thinking

The seven THREAD tenets were selected for their comprehensive representation of the dual facets essential to fashion thinking: critical thinking and design cognition. Fashion thinking is a blend of analytical skills and creative abilities (Nixon & Blakely, 2012; Aspers & Godart, 2013; Pecorari, 2016; Buckley & Clark, 2018), described as both an epistemology and a methodology for creating visual and material representations of time and place (Nixon & Blakely, 2012; Aspers & Godart, 2013; Pecorari, 2016; Buckley & Clark, 2018). It aligns with Cross's (2006) concept of 'designerly ways of knowing,' where designers translate meaning through hands-on experience with materials and objects (Mazzarella et al., 2019).

Fashion thinking is understood as a framework of critical thought and problem-solving applied to fashion design (Dieffenbacher, 2021), characterized by "a paradigm of critical thought and creative agency utilizing technology, story, experimentation, and open sourcing to add meaning and value to products and services" (Nixon & Blakely, 2012, p. 157). Design cognition involves creating and interpreting three-dimensional fashion artifacts (Swindells & Almond, 2016), paralleling sculpture through shared elements like touch, mimicry, and empathy. A holistic understanding of fashion thinking requires studying both critical thinking and design cognition, as they collectively inform the analytical and creative processes integral to fashion design practice.

Fashion Thinking: Critical Thinking and Design Cognition

Critical thinking and design cognition are complementary aspects of fashion thinking, each contributing unique skills to the design process. Critical thinking provides a framework for evaluating and refining design ideas, ensuring they meet functional, aesthetic, and ethical criteria (Nixon & Blakely, 2012). It involves analytical and problem-solving capabilities (de Wet, 2015), helping designers address technical constraints, budget limitations, and market demands (Butler-Young, 2022). This includes analyzing feasibility, conducting market research, and identifying opportunities for improvement.

Design cognition, on the other hand, fuels creative exploration and experimentation, allowing designers to push the boundaries of fashion through tactile exploration, mimicry, and empathy (Swindells & Almond, 2016). It involves intuitive knowing, hands-on experimentation, and a tacit aesthetic sense, enabling designers to conceptualize and refine their creations (Cross, 2006; Treadaway, 2007). Together, design cognition and critical thinking form a balanced approach to fashion thinking, blending artistic vision with strategic analysis.

The THREAD framework's tenets map to either critical thinking or design cognition (Figure 2.1). Problem Solving, Reflexivity, and Individual Agency embody critical thinking by emphasizing systematic approaches to challenges, self-awareness in the creative process, and analytical approaches to design. These tenets highlight cognitive processes that underpin thoughtful and reflective practice, ensuring designers can navigate complex problems, critique their work, and harness their unique perspectives.

Tacit Knowledge Application, Spatial Visualization, Haptic Memory, and Creativity capture the essence of design cognition. Tacit Knowledge Application underscores the unspoken, experiential knowledge crucial for intuitive decision-making and craftsmanship (Hay et al., 2020). Spatial Visualization is essential for conceptualizing and manipulating designs in three-dimensional space (Beaty et al., 2018). Haptic Memory relates to tactile experiences that inform material choices and garment construction. Creativity drives innovation and originality in fashion. Focusing on these tenets, the literature review illuminated how the interplay between critical thinking and design cognition forms the foundation of fashion thinking, offering a holistic framework that underscores the importance of both analytical and imaginative processes in this field.

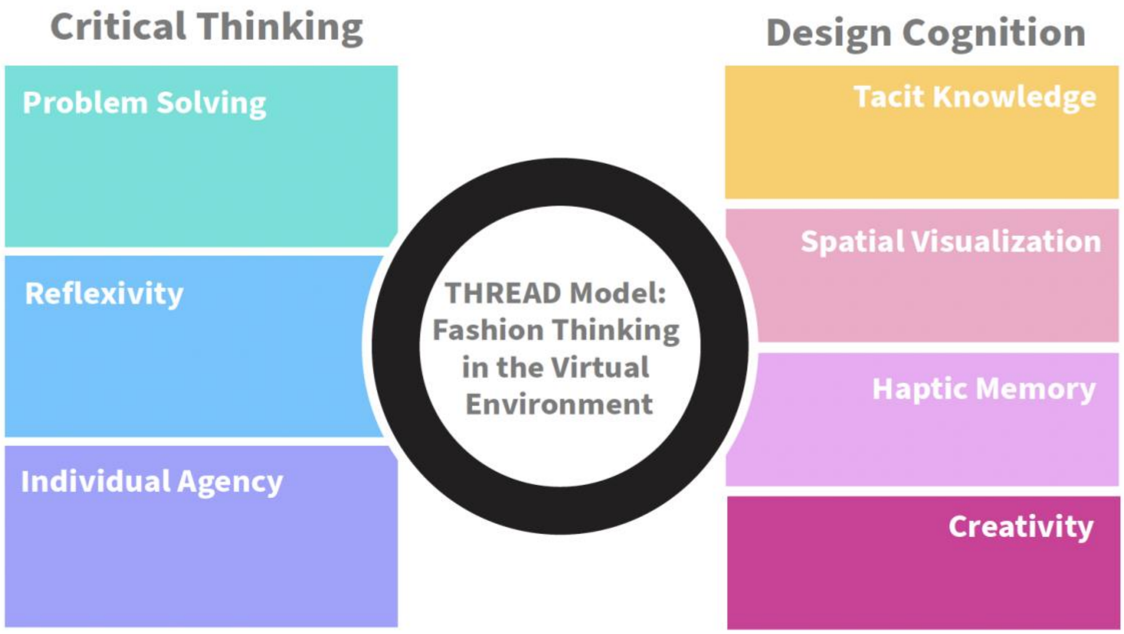

Figure 2.1

Graphic Representation of the THREAD Model

Meta-Narrative Literature Review

This study utilized a meta-narrative review methodology (Greenhalgh et al., 2005; Wong et al., 2013) to explore this rich literary landscape and formulate the THREAD model. A meta-narrative review is suitable for this research because it addresses topics conceptualized in diverse ways and studied by various researchers (Wong et al., 2013). This approach combines traditional literature review with rich description and theory construction, providing scholarly summary along with interpretation and critique (Greenhalgh et al., 2005; Greenhalgh, Thorne, & Malterud, 2018). Meta-narrative reviews emphasize "sense making over cataloguing" and aim to produce novel frameworks through careful study (Dixon-Woods et al., 2005; Greenhalgh et al., 2009, p. 730). They often aim for theory or framework development (Baumeister & Leary, 1997). This theoretical work intended to a) survey the state of knowledge on virtual fashion thinking by incorporating findings from various disciplines and b) propose the THREAD framework, outlining the overarching tenets from the literature review and analysis.

The meta-narrative review process began with a comprehensive examination of existing literature to identify the key components of fashion thinking in the virtual environment. This involved an iterative process of searching, selecting, and synthesizing studies from a wide range of sources and disciplines. The goal was to capture the depth and breadth of research on both critical thinking and design cognition as they pertain to fashion thinking, particularly within virtual environments. This search involved literature from disciplines including the following: a) educational theory and pedagogy, b) design studies, c) creativity and innovation in education, d) computer science and human-computer interaction (HCI), e) psychology and cognitive science, f) engineering and mathematics, g) Digital Literacy, and h) technology in education.

Criteria for Literature Selection

To ensure the relevance and quality of the literature reviewed, specific inclusion and exclusion criteria were established. The inclusion criteria comprised of studies published in peer-reviewed journals or reputable conference proceedings, research focused on empirical studies, theoretical papers, and comprehensive reviews that were identified as valuable in the contribution to the understanding of the cognitive and creative processes in fashion design, and studies that explore virtual or 3D design environments from other disciplines. On the other hand, exclusion criteria involved articles not available in English, studies lacking rigorous methodology or clear relevance to the key themes, and publications older than 20 years unless they were seminal works that significantly influenced the field.

Search Strategy

The search strategy involved sourcing literature from several academic databases, including Google Scholar, JSTOR, and PubMed. Keywords used in the search included “fashion thinking”, “design cognition”, “critical thinking in design”, “engineering design cognition”, “learning technologies”, “educational innovation”, “virtual fashion design”, “industry 4.0”, "3D design environment”, “creativity in fashion design”, “digital literacy”, “product innovation and engineering”, “virtual and augmented reality”, “kaleidoscopic thinking”, “spatial visualization and engineering graphics”, and “cognition in 3D”. These keywords were combined using Boolean operators to refine search results and ensure comprehensive coverage of relevant literature. From the selected studies, re-occurring themes central to the intersectional research area were identified. This process involved coding the literature to highlight aspects of critical thinking and design cognition in the 3D environment, mapping these onto the potential tenets of fashion thinking.

Parallel Discipline Search and Data Synthesis

While there is limited academic discussion on pedagogical fashion design as an epistemological form of critical thinking, the literature suggests that critical thinking is both inherent and teachable within the discipline (Piaget, 1952). The lack of scientific inquiry has led to misunderstandings about fashion design, fashion design pedagogy, and the role of 3D simulation software in this discipline. In contrast, academic subjects such as physics, mathematics, chemistry, civil engineering, and material science have demonstrated that 3D simulation software encourages the development of critical thinking skills (Suryanti et al., 2020;

Syawaludin et al., 2019; Tercete et al., 2017; Astuti et al., 2020). By integrating methodologies and insights from various fields, the THREAD model aims to bridge the gap in understanding and pedagogy, fostering a comprehensive approach to 3D fashion thinking. Table 2.1 presents an overview of the number of citations incorporated from each discipline explored in the meta-narrative literature review, justifying the inclusion of each tenet in the THREAD framework. By incorporating research from fields where 3D simulation software has been systematically studied and validated, the THREAD framework is grounded in empirically sound findings about the link between critical thinking and design cognition with the virtual environment.

Extracted findings were synthesized through thematic analysis, identifying common themes across studies from various disciplines. This led to clustering findings around seven core tenets (Table 2.1): Problem Solving, Reflexivity, Individual Agency, Tacit Knowledge Application, Spatial Visualization, Haptic Memory, and Creativity. Each tenet was derived from recurring concepts in the literature, forming the cognitive and critical dimensions essential to fashion thinking.

Table 2.1

THREAD: Interdisciplinary Justification of Tenets by Citation Number

Categories & Sub-Categories	**Problem-Solving**	**Reflexivity**	**Individual Agency**	**Tacit Knowledge**	**Spatial Visualization**	**Haptic Memory**	**Creativity**
Educational Theory and Pedagogy	8	10	9	7	2	1	5
Critical Thinking	3	9	6	6	2	1	1
Teaching Methods & Learning Strategies	4	2	2	1	2	1	5
Self-Regulated Learning	1	2	6	5	1	1	2
Educational Technology & Innovation	1	2	3	1	2	2	1
Creativity & Innovation in Education	3	2	2	2	2	1	1
Design Education & Design Thinking	4	2	3	3	4	2	1
Fashion Thinking	3	2	2	3	2	2	2
Design Thinking- Fashion & Apparel Design	2	2	2	4	3	4	2
Creativity	1	1	2	1	1	1	2
Kaleidoscopic Thinking	3	2	3	1	1	1	2

3D Learning	1	1	5	1	2	2	1
Psychology & Cognitive Science	3	4	3	3	8	3	3
Cognition in 3D	1	1	2	0	3	3	1
Problem Solving & Critical Thinking	2	4	2	1	4	1	2
Computer Science & HCI	4	4	1	2	9	7	1
Industry 4.0	3	3	3	3	4	3	2
Visualization & Graphics	1	1	1	1	4	3	1
Virtual & Augmented Reality	2	1	3	2	3	5	1
Engineering & Mathematics	2	1	4	1	6	2	2
Spatial Visualization & Engineering Graphics	1	1	4	2	5	4	1
Product Engineering & Innovation	2	2	2	1	2	2	3
Digital Literacy & Technology in Education	4	2	4	3	2	1	4
Digital Literacy & E-Learning	3	1	4	1	2	1	3
Innovation Management	3	1	2	2	0	1	1
Design Studies	15	6	1	6	3	5	7
Fashion Design	4	1	3	3	2	0	2
Graphic Design	1	1	1	1	1	0	2
Architecture	2	1	0	1	4	4	1
Arts	3	3	1	1	1	1	2
Textile Design	2	1	2	1	1	2	1

Note. This chart justifies the inclusion of each tenet within the THREAD framework of 3D fashion thinking—Creativity, Tacit Knowledge, Reflexivity, Visualization, Problem Solving, Individual Agency, and Haptic Memory—by providing the number of citations from each relevant discipline and domain that were pulled to inform the corresponding tenet.

THREAD: Meta-Narrative Literature Review

Comprised of seven tenets sectioned into two areas including critical thinking and design cognition, the framework proposed is an outcome of a meta-narrative literature review. The THREAD Framework intends to outline the components of fashion thinking relevant to the field of fashion design in the virtual environment and to categorize critical thinking and design cognition behaviors and skills that are observable in 3D design activities. The theoretical framework, "THREAD", reflects a deliberate abstraction of the cognitive processes inherent in the fashion design learning environment. The term "THREAD" serves as a metaphorical representation of the interconnectedness and continuity of thought throughout the design process. Just as a thread is woven through fabric, connecting various fibers to form a cohesive whole, the cognitive processes represented by each tenet in the THREAD model thread through the designer's mind.

THREAD: Critical Thinking

The THREAD framework emphasizes critical thinking as a fundamental aspect of fashion thinking, comprising three essential tenets. Problem-solving lies at the core, as designers adeptly navigate technical constraints, budget limitations, and market demands, strategically developing solutions to overcome challenges throughout the design process (de Wet, 2015). Reflexivity encourages designers to engage in critical self-awareness, examining biases, assumptions, and creative processes to continuously refine their approach (Butler-Young, 2022). Lastly, Individual Agency underscores the active role of designers in shaping the fashion landscape, empowering them to make deliberate choices that drive innovation and resonate with consumers (Dieffenbacher, 2021). These tenets collectively contribute to the THREAD framework's focus on the critical thinking element within fashion thinking. The THREAD framework emphasizes critical thinking in fashion thinking through three tenets: problem-solving, reflexivity, and individual agency. These tenets help designers navigate constraints, engage in critical self-awareness, and make deliberate choices to drive innovation and resonate with consumers.

Problem-Solving

Critical thinking as a mechanism for generating new answers and ideas through problem-solving methods emerged prominently in architectural and design studies following the Bauhaus model (Meroni et al., 2018). Established by Walter Gropius in 1919, the Bauhaus school aimed to blur the lines between pure and applied art, technology, and theory. Pedagogical methods were employed to develop students' observational, analytical, and critical thinking skills through problem identification, solution finding, and industry feedback incorporation to refine design approaches (Chircop, 2021). The Bauhaus model values design as a fusion of theory and praxis, centered on problem-solving.

Design is often conceptualized similarly to Dewey's problem-solving model (1993), where designers simultaneously construct and solve design problems. "Design knowledge resides as much in the processes as it does in the product" (Gully, 2010, p.41). The iterative process of conceptual sketching, freeform patternmaking, and virtual draping fosters internal thinking relevant to critical thinking. Product design and development are seen as sequences of problem-solving cycles, each beginning with "problem recognition and goal definition" and resolved through experimentally exploring design alternatives (Thomke & Fujimoto, 2000, p. 130). Problem-solving is central to critical thinking as it involves crafting solutions and reflective analysis (Halpern, 1993).

Oh and Jonassen (2007) define problem-solving as a creative process utilizing both divergent and convergent cognition through three stages: transformation, clarification, and implication. In the transformation stage, students explore ideas and formulate solutions. In the clarification stage, they articulate challenges and refine their vision (Puccio et al., 2004). The implication stage involves planning and assessing the solution's acceptance (Puccio et al., 2004). Student designers adopt a cause-and-effect approach, understanding design as core problem-solving (Dorst & Reymen, 2004). Divergent thinking involves an extensive search for ideas, while convergent thinking focuses on selecting workable solutions (Oh, 2017). Creative problem-solving is intuitive, requiring specific cognitive skills for generating and refining ideas into practical solutions (Oh, 2017). Teaching problem-solving in apparel design is key to successful innovation and realizing students' creative potential.

3D simulation software aids problem-solving by allowing designers to build and test virtual models early in the development process, enhancing efficiency and effectiveness (Fixson & Marion, 2012). It promotes problem-solving by enabling designers to identify design issues, make modifications, and evaluate impacts in real time. This iterative process encourages critical thinking by challenging designers to analyze design decisions, consider alternatives, and find creative solutions.

Reflexivity

Critical thinking hinges on the designer's ability to engage reflexivity in the iterative design process. Reflexivity for practice encourages the surfacing and criticizing of knowledge that emerges silently, by way of repetitive specialized practice (Schön, 1983). Reflexivity is:

> An artist-like process that occurs when a creative practitioner acts upon the requisite research material to generate new material which immediately acts back upon the practitioner who is in turn stimulated to make a subsequent response. (Haseman & Mafe, 2009, p. 219).

One cannot discuss reflexivity without referencing Schön's Reflective Practitioner (1983). Schön's (1983) work focused on reflection-on-action and reflection-in-action concepts that suggest experiential learning happens when the learner is involved with the work itself. According to Lamb and Huttlinger, reflexivity is actually a kind of critical thinking that reflects the exchange and interaction between investigator and research environment (1989). In this way, reflexivity in art and design might best be described as the exchange between designer and artifact. The most simplified definition of reflexivity proposed by scholars is simply researcher self-awareness and self-analysis throughout the investigative endeavor (Berger, 2013; Finlay, 2002; Pillow, 2003). “Design is converting the actual to the preferred. It is the conversation with the materials of a situation” (Schön, 1983, p. 77).

Research has been conducted on reflective methods across an array of disciplines, but creative studio design is largely left out (Coorey, 2012). In the fashion design classroom, students are typically encouraged to critique the complete designed artifact, largely ignoring the thinking that produces the design solution. Based on Schön’s (1983) conception of reflexivity, Coorey (2012) proposed a framework involving process books, written analysis, and visual process maps to help student designers become independent learners and creative thinkers. The study found that these methods significantly enhanced students' critical thinking skills and reflective practices. Data showed improved critical thinking during critique sessions, confirming the importance of reflection and adjustment in the creative process (Coorey, 2012). Reflexivity is a vital aspect of THREAD's critical thinking model due to its practical relevance, addressing a gap in creative studio design education by emphasizing reflective processes.

Individual Agency

The final tenet of critical thinking within the THREAD framework is individual agency, a crucial aspect that resonates particularly in art and design disciplines. Here, the weighty responsibilities of creating, providing solutions, and interpreting the abstract in contemporary society underscore the significance of critical thinking skills. Individual agency, integral to critical thinking, is defined as the proactive, purposeful, and effective pursuit of valued goals and desired outcomes (Chuter, 2020, p. 1). In other words, agency is grounded in motivation and is a student’s learned ability to display a growth mindset, grit, and personal ownership over their own learning (Pieratt, 2017). Individual agency shapes the process of learning most notably through the associated motivational component (Ford, 1992; McCombs & Marzano, 1990) and the perception of the learning experience and knowledge to be more self-relevant (Wolters, 1998; Zimmerman, 2001).

Students develop more agency in the virtual classroom setting (VCS) than in a traditional classroom setting, as the instructor takes more of a content facilitator role than that of a gatekeeper of knowledge (Bose, 2003; Goodyear et al., 2001; Parise, 2000; Smith et al., 2001). When learning virtually, students take on a proactive versus reactive role in their knowledge acquisition, where learning takes place mostly through projects and assignments (Boynton, 2002). With agency as the students' power to choose what happens next (Lindgren & McDaniel, 2011), learning apparel design in 3D software facilitates this self-determination and sense of purpose. The capacity of 3D simulation software to provide content that is manipulable, and dynamic makes it uniquely suited to supporting student exercise of individual agency, underscoring the necessity to include this tenet in the THREAD framework of 3D fashion thinking.

THREAD: Design Cognition

Together, critical thinking and design cognition form complementary aspects of fashion thinking, each contributing unique perspectives and skills to the design process. Design cognition, as it is conceptualized within the THREAD framework of 3D fashion thinking, fuels the creative exploration and experimentation essential for pushing the boundaries of fashion design through the senses (Swindells & Almond, 2016). Design cognition within the THREAD framework centers on four core tenets, namely Creativity, Tacit Knowledge, Spatial visualization, and Haptic Memory. Creativity serves as the cornerstone, allowing designers to generate novel ideas and innovative solutions to design challenges (Nielsen & Thurber, 2020). Tacit knowledge underpins this process, drawing upon intuitive understanding and expertise developed through practice and exposure (Sternberg & Hedlund, 2002; Sternberg et al., 2000). Spatial visualization skills enable designers to mentally manipulate and envision three-dimensional forms, facilitating effective conceptualization and refinement of designs (Chen, 2004). Haptic memory further enhances this process, as designers leverage sensory experiences and tactile memories to inform their creative decisions (Sun & Parsons, 2015). Together, these four tenets form the bedrock of design cognition within the THREAD framework, fostering intuitive creativity, informed decision-making, and effective design execution.

Design Cognition

Design cognition explores the cognitive processes and mental models shaping designers' creative thinking, including the intuitive understanding of design principles, iterative ideation, and the application of tacit knowledge (Hay et al., 2020). It involves dual-process models of creativity, balancing spontaneous memory retrieval with deliberate idea evaluation (Beaty et al., 2018), and is further enriched in fashion by the interplay of creativity, embodiment, and digital technologies (Hayles, 2012; Lupton, 2017). Theories for design pedagogy include Beckman and Barry's four-phase cycle (experiencing, reflecting, thinking, acting) (Beckman & Barry, 2007) and the Hasso Plattner Institute's six components (understand, observe, point of view, ideate, prototype, test) (Carroll et al., 2010). Embracing design cognition in classrooms enhances students' critical thinking (Ingalls Vanada, 2014). Scholars like Herbert Simon define it as transforming existing conditions into preferred ones (Simon, 1996), while others emphasize reasoning and hands-on experience (Cross, 2006; Lawson, 2005; Dorst, 2011), and Krippendorff highlights meaning creation as central to design cognition (Krippendorff, 2006)

Design Cognition within Fashion Thinking

Recent studies highlight the need to understand fashion's disciplinary knowledge for developing suitable methodologies (Finn, 2014; Ræbild, 2015), challenging the distinction between critical thinking and design cognition. They propose that fashion design’s unique characteristics, such as kaleidoscope thinking and meaning-making, expand its scope (Kimbell, 2011; Manzini & Coad, 2015; Manzini, 2016). Design cognition in fashion thinking involves social and aesthetic elements, with a feedback loop between producers and consumers that decodes behavior, values, and aesthetics (Nixon & Blakely, 2012). This loop fosters dynamic interactions, informing producers' decisions and shaping fashion trends (Whitty, 2021). The fashion industry acts as tastemakers, using design cognition to interpret patterns and preferences, creating culturally resonant products (Currid-Halkett, 2009; Nixon & Blakely, 2012).

Creativity

Creativity is a key element of design cognition and one of the seven tenets of the THREAD framework (Jackson, 2003). Creativity in design involves both divergent and convergent models of cognition (Jackson, 2003), and is defined as the ability to bring new and valuable things into being (Nielsen & Thurber, 2020) and to generate new ideas and apply them to practice (Robinson & Aronica, 2016). In fashion design, creativity is the process designers use to generate novel and valuable ideas, solutions, and products (Sarkar & Chakrabarti, 2011).

Black et al. (2015) present a Conceptual Model of Creative Thinking in Apparel Design, which, like a model from music creativity research (Webster, 1987), balances aesthetic vocabulary with technical knowledge of textiles, construction, and visual design elements. This model involves phases of preparation, incubation, illumination, and verification (Wallas, 1926), requiring students to evaluate consumer needs, conduct market research, and balance convergent and divergent thinking. The third phase, Consensual Assessment and Evaluation of Applicability, involves re-evaluating product intention using domain-specific knowledge and convergent thinking (Black et al., 2015). Including creativity in any framework of fashion thinking is imperative because it fosters innovation and helps learners approach problems with originality and imagination. The ability to innovate and adapt to new challenges, skills requiring divergent thinking, is crucial in the context of advancing technology.

Divergent Thinking

Divergent thinking is one of the foundational elements of creative thinking (Koberg & Bagnall, 1995; Nusbaum & Silvia, 2011). Guilford found that divergent thinking enhances artistic ability, depending on the content of the specific discipline (1957). Guilford outlined four divergent thinking abilities: fluency, flexibility, originality, and elaboration (1957). Black, Freeman, and Stumpo applied Guilford's four divergent thinking abilities to their Conceptual Model of Creative Thinking in Apparel Design (2015) to create apparel design divergent thinking abilities. These include apparel design fluency, which is the number of ideas or design responses, apparel design flexibility, which is the number of garment types and categories, apparel design elaboration, which is the amount of design detail executed, and apparel design originality, or the uniqueness of design execution (Black et al., 2015). The four divergent thinking abilities outlined in Guilford's model, supported by the vast evidence of the enmeshment of divergent thinking with creativity, support the inclusion of divergent thinking in the THREAD framework.

Tacit Knowledge

Tacit knowledge, gained through experience, is foundational to THREAD's design cognition duality. It represents practical intelligence (Sternberg & Hedlund, 2002; Sternberg et al., 2000) and influences problem-solving and discretionary judgment (Cox III et al., 2008).

Sternberg's work highlights three features of tacit knowledge: it is extracted from experience, procedural and context-specific, and relevant to individual goals (Sternberg, 1997; Sternberg & Horvath, 1999; Sternberg et al., 1995; Sternberg et al., 2000). Tacit knowledge, which is deeply embedded in physical objects, is central to craft-based production and design thinking. It is essential in fashion design processes like draping, patternmaking, and 3D software use, learned through sensory interactions and tool manipulation (Sgro, 2018). Sennett (2009) notes that high skill levels involve an interplay between tacit knowledge and explicit awareness, where craft quality emerges from judgments based on tacit habits.

The misalignment of designer intent with modern product development highlights the value of tacit knowledge (Siu & Dilnot, 2001). Inadequate design representation often results from ignoring tacit knowledge (Petroski, 1996). Fashion design, like jewelry design, suffers from representation failures, but 3D technology helps bridge this gap by synchronizing design and making processes, reducing communication errors (Siu & Dilnot, 2001). Including tacit knowledge in THREAD for 3D fashion thinking acknowledges that design knowledge extends beyond the codifiable, as Anni Albers (1944) describes it as "an intelligence expressing itself in other means than words" (p. 27). This blend of knowledge through doing is crucial for advancing fashion design (Finn, 2014).

Visualization

Visualization, and specifically spatial visualization, is a key tenet of the THREAD framework's design cognition paradigm. To fully grasp spatial visualization, it is necessary to first discuss visualization as a whole. Visualization can be defined as a form of information processing that enables the transformation of information from one representation to another (Chen & Golan, 2016). Historian of imagery and visuals, Barbara Maria Stafford (1997) suggests that it is the visualization of science that allows us to make the fundamental connection between seeing and knowing. North (2006) proposes that the purpose of visualization is to achieve insight, which he characterizes as: complex, deep, qualitative, unexpected, and relevant. North proposes that visualization can be evaluated through determination of how well visualization achieves insight.

Insight that is complex involves the given cognitive elements in a synergistic way; Insight that is deep culminates over time to create depth. Qualitative insight is subjective and can result in various levels of resolution. Insight that is unexpected is unpredictive, dynamic, and creative; and finally, relevant insight is embedded in the knowledge and achieves domain impact (North, 2006). According to Halpern, one of the most salient ways to improve creative thinking skills is to learn techniques of visualization and cognitive representation (1993). There lies a complete intersectionality between creativity and critical thinking, of which visualization is at the heart. Creativity is exploration through visual means and merges on exploring possibilities and considering alternatives (Moeller et al., 2013). With North's framework for assessing visualization in mind, visualization as a tenet of design cognition for fashion thinking could be identified and understood in the 3D apparel design space.

Design ideas are communicated through visualization at all stages of the apparel design process. Preliminary croquis sketches help conceptualize ideas like silhouettes, color, print, and fabrication, followed by detailed technical drawings in CAD software to outline construction and fabric placement. These technical visualizations are then refined, sometimes in 3D, to create prototypes essential for industry production or student assessment, leading to the final garment construction. 3D simulation software, a core visualization tool, enables designers to experience functional realism by manipulating computer graphics realistically (Ferwerda, 2003). 3D simulation software promotes analysis by providing a virtual environment for detailed design iteration and assessment from various perspectives, merging conceptual ideation with technical acumen (Chen & Golan, 2016). This software enhances student designers' understanding of fit, silhouette, and aesthetics, improving their skills without wasting materials (Hwang & Hahn, 2017; Park et al., 2010), thus fitting seamlessly into the THREAD framework.

Spatial Visualization

Spatial visualization, the ability to cognitively manipulate the complex relationships between 3D objects and space, is a crucial skill in many industries. Understanding the relationships of elements relative to each other is central to spatial visualization (Salthouse et al., 1990). The 3D learning environment enables learners to visualize abstract concepts in an immersive and scalable way, leveraging natural human perception (Wann & Mon-Williams, 1996). In architectural design, spatial manipulation of 3D objects is essential for visual communication (Chen, 2004). In engineering, 3D graphics instruction significantly improves students' spatial visualization skills (Braukmann, 1991). This practice has shown value in fields like engineering and mathematics, encouraging complex mental manipulation of objects (Lowrie et al., 2019; Strong & Smith, 2002).

In apparel design, spatial visualization is critical as designers must transform 2D patterns into 3D garments (Park et al., 2010). Park, Kim, and Sohn found that 3D simulation technology effectively improves students' visualization skills (2010). Workman and Zhang observed that students trained in both CAD and traditional patternmaking scored higher in spatial visualization than those with only one type of training (1999). Spatial visualization is integral to fashion design students' success, requiring them to envision objects from different perspectives to recreate them in real time (Power, 2013). The incorporation of 3D simulation software in fashion design education is crucial for developing spatial visualization skills, providing an environment to transform 2D patterns into 3D garments (Park et al., 2011). Positioned at the intersection of knowing and doing, spatial visualization is a fundamental tenet within THREAD's design cognition framework.

Haptic Memory

Haptic memory is highly engaged when working with 3D simulation software. Haptic devices, such as 3D mice, tablets, and stylus pens, rely on the force feedback concept, transmitting pressure, force, or vibrations to enable users to sense changes in the virtual environment (Blade & Padgett, 2002). These devices provide more freedom in panning, zooming, rotating, and manipulating 3D objects in the simulation space (Sun & Parsons, 2015). Haptics, derived from the Greek root "haptios," refers to the sense of touch that helps us perceive the boundaries of our physical being (Kern et al., 2023). Immanuel Kant (1724-1804), an influential philosopher in the fields of aesthetics, ethics, and knowledge purported that touch generates knowledge from experience while contextualizing spatial environmental awareness:

> This sense is the only one with an immediate exterior perception; due to this it is the most important the most-teaching one, but also the roughest. Without this sensing organ we would be able to grasp our physical shape, whose perception the other two first class senses [sight and hearing] have to be referred to, to generate such knowledge from experience (2009, p. 389).

According to "Engineering Haptic Devices," haptic systems can be divided into device systems, which produce an unchanging effect, and active, reconfigurable systems, which change based on interaction with the virtual environment (Kern et al., 2023). 3D simulation software for fashion design follows the latter model. Material researchers have created a framework presenting four components of material experience as essentials of haptic cognition development: understanding the material, creating materials experience vision, manifesting materials experience patterns, and designing material/product concepts (Karana et al., 2015). This framework highlights the intersection of materials, paramount in fashion, to haptic sense development as a key component of innovative design cognition. As haptic memory is a type of tactile consciousness drawn from past experience working with physical objects, it is closely tied to material thinking, involving "thinking through the hand manipulating a material" (Nimkulrat, 2012). Materials are not mere passive tools but means of embodiment with artistic intelligence, connecting the mind to the hands and eyes (Carter, 2005). The pedagogy of haptic model-making is described as an out-of-body experience that stimulates the body, draws on life-long memories, engages with the body's ability to learn and transform, and recognizes its ability to imagine and create new possibilities (Macklin, 2013). Haptic memory is crucial in the design process, whether physical or virtual. It is highly engaged when working with 3D simulation software, highlighting the intersection between 3D simulation, fashion design pedagogy, and fashion thinking, firmly situating haptics in THREAD's design cognition framework.

THREAD: In Conclusion

A meta-narrative literature review elucidated seven larger categories of fashion thinking, which were then divided into two key aspects: critical thinking and design cognition. These combined to form the THREAD framework, encapsulating the essence of fashion thinking. This framework emphasizes the symbiotic relationship between critical thinking and design cognition, highlighting their unique contributions to the fashion design process. Critical thinking provides a structured approach to evaluating and refining design ideas, ensuring they meet functional, aesthetic, and ethical criteria (Nixon & Blakely, 2012). Rooted in the left brain, critical thinking involves analytical and problem-solving capabilities (de Wet, 2015). Problem Solving, Reflexivity, and Individual Agency embody critical thinking in the THREAD model and designers employ critical thinking to address technical constraints, budget limitations, and market demands, developing strategic solutions (Butler-Young, 2022). This involves analyzing feasibility, conducting market research, and identifying opportunities for improvement. By evaluating different approaches, designers ensure their creations meet desired objectives and resonate with the target audience.

Conversely, Tacit Knowledge, Spatial Visualization, Haptic Memory, and Creativity capture the essence of design cognition. Design cognition is rooted in the right brain and fuels creative exploration and experimentation. It allows designers to push the boundaries of fashion through tactile exploration, mimicry, and empathy (Swindells & Almond, 2016). Design cognition involves intuitive knowing, hands-on experimentation, and a tacit aesthetic sense, enabling designers to conceptualize and refine their creations (Cross, 2006). This process relies on intuition and empathy, guiding designers in envisioning innovative concepts and exploring unconventional ideas (Treadaway, 2007). Together, design cognition and critical thinking form a balanced approach to fashion thinking, blending artistic vision with strategic analysis. This synergy allows designers to navigate the complexities of the fashion industry, transforming abstract ideas into tangible, innovative, and successful creations.

Discussion

By mapping out the relationships between cognitive and creative processes, THREAD offers a structured approach to exploring how designers operate within virtual environments. This is particularly relevant given the increasing adoption of 3D simulation software in fashion education, which presents new opportunities and challenges for developing critical and creative skills (Park et al., 2010; Siu & Dilnot, 2001). The application of THREAD in a virtual fashion design learning environment has several implications. First, it provides a detailed lens through which educators and researchers can analyze the cognitive and creative processes involved in 3D fashion design. This analysis can inform the development of educational tools and strategies that enhance students' ability to think critically and creatively. For instance, by understanding how tacit knowledge and haptic memory influence design thinking, educators can create learning experiences that emphasize hands-on interaction and experiential learning, even in virtual settings (Gully, 2010; Nixon & Blakley, 2012). Moreover, the framework highlights the importance of reflexivity and individual agency in fostering a proactive and growth-oriented mindset among student designers. By encouraging students to reflect on their design processes and take ownership of their learning, educators can cultivate the skills necessary for success in a rapidly evolving industry (Boynton, 2002). The focus on problem-solving also underscores the need for educational approaches that emphasize iterative design and experimentation, allowing students to build and test virtual models early in the development process (Thomke & Fujimoto, 2000). The integration of creativity within the THREAD framework emphasizes its central role in both critical thinking and design cognition. Creativity is recognized as a key element in the critical thinking process, essential for generating new ideas in fashion design (Jackson, 2003; Sarkar & Chakrabarti, 2011). The inclusion of creativity ensures that the framework not only addresses analytical and reflective aspects but also fosters an environment where innovation and originality can thrive.

Future research should explore the circumstances in which the THREAD framework can be most effectively adopted and the potential implications of its application. This includes investigating how the framework can be tailored to different educational contexts and disciplines within 3D fashion design, as well as examining its impact on students' cognitive and creative development. Additionally, research should consider how advancements in technology, such as improved 3D simulation software and virtual reality, can further enhance the applicability and effectiveness of the THREAD framework.

In conclusion, the THREAD framework represents a significant contribution to the understanding of fashion thinking in the context of 3D fashion design pedagogy. By integrating critical thinking and design cognition through seven key tenets, the framework provides a robust and nuanced perspective on the cognitive and creative processes that underpin effective design practice. Its application in virtual learning environments offers valuable insights for educators, researchers, and practitioners, paving the way for innovative approaches to fashion design education that meet the demands of a rapidly changing industry.

Limitations

While the THREAD framework offers a comprehensive perspective on the cognitive and creative processes involved in 3D fashion design, several limitations must be acknowledged. While the framework is conceptually sound, its practical application and effectiveness in real-world settings requires empirical validation. Additionally, critical thinking is a multifaceted and complex construct, resulting in some difficulty in encapsulation of all aspects of critical thinking as it is situated in 3D simulation software usage for undergraduate fashion design education. And, as technology continues to evolve and emerging designers are required to keep pace with the rapid advancements, the framework will likely have to be updated and adjusted as new tools and discoveries are made. Additionally, the meta-narrative literature review approach, while extensive, may not encompass all relevant studies and perspectives within the diverse fields of critical thinking, design cognition, and 3D fashion design. The selection of literature might be biased towards certain methodologies or theoretical perspectives, potentially overlooking significant contributions from less prominent or emerging research areas. Second, the applicability of the THREAD framework across different educational contexts and disciplines within fashion design remains to be thoroughly tested. The framework was developed primarily with a focus on virtual fashion design learning environments. As such, its relevance and effectiveness in traditional, hybrid, or other innovative learning settings are not yet fully understood and warrant empirical investigation.

Additionally, the reliance on 3D simulation software as a central element of the framework introduces potential technological constraints. Variations in access to and proficiency with such technologies among educational institutions and students could impact the framework's implementation and outcomes. Also, the rapidly evolving nature of technology in fashion design means that the framework may require continuous updates to remain relevant and effective. By addressing these limitations through further research and iterative refinement, the framework can be strengthened and adapted to meet the evolving needs of the fashion design discipline.

Conclusion

The THREAD framework emerges as a pioneering approach to understanding and enhancing the cognitive and creative processes in 3D fashion design pedagogy. By synthesizing insights from a meta-narrative literature review, this framework integrates seven essential tenets into a cohesive model that addresses both critical thinking and design cognition. This dual focus provides a robust foundation for exploring how these cognitive elements interplay to form a comprehensive view of fashion thinking within virtual learning environments. The application of the THREAD framework offers significant potential for advancing fashion design education by providing educators, researchers, and practitioners with a detailed lens through which to analyze and enhance the learning process. It highlights the importance of fostering both analytical and creative skills, ensuring that students are well-equipped to navigate and innovate within the increasingly digital landscape of the fashion industry

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CHAPTER 3

PAPER 2: FASHION THINKING IN INDUSTRY 4.0: 3D SIMULATION SOFTWARE AND CRITICAL THINKING

Overview

This study explores student fashion designers' critical thinking processes within 3D simulation software through the application of the relevant tenets of the framework, THREAD. This work discusses the implementation of 3D simulation software as an educational tool for fostering critical thinking skills within the broader denotation of fashion thinking within undergraduate design pedagogy. In order to determine whether fashion design pedagogy situated in the 3D space was conducive to critical thinking skill development, verbal protocol data was analyzed and aligned with the tenets of a developed model of critical thinking for 3D fashion design, the THREAD framework. The central research question is: how does the virtual environment produced by 3D simulation software engage critical thinking skills in the fashion design process? Findings revealed that CLO 3D fosters problem-solving by enabling iterative design and intuitive decision-making, though its reactive workflow can sometimes lead to inefficiencies. Reflexivity manifested in real-time refinement, but rapid adjustments were found to sometimes replace deeper critical analysis, highlighting the need to balance experimentation with evaluation. Additionally, this study found that CLO supports individual agency by encouraging creative exploration and autonomous decision-making, though maintaining a balance between independence and deeper design analysis remains crucial.

Introduction

Fashion design graduates must have a foundational knowledge base of 3D technologies as the industry is shifting towards simulated product development and as learning to think critically becomes recognized as one of the most important skills acquired in fashion school. Observing student designers' critical thinking processes within the virtual environment is essential to furthering the discipline. This study intends to validate the role of critical thinking in undergraduate fashion design education by analyzing critical thinking skill acquisition as it relates to the increasingly necessary learned intelligence of digital literacy. This work will also contribute to creating a robust knowledge repository that fashion academia can utilize to better equip students for success in an industry that increasingly relies on simulation and visualization tools and critical thinking ability.

Justification

As we move into the digital industrial era, student designers will be expected to enter the workforce with digital intelligence, which can be understood as the skills, abilities, and competencies central to navigating and succeeding in the digital environment. Researchers have identified a couple of essential characteristics of digital intelligence. Of specific relevance to 3D simulation software in the fashion design context, the following were identified as essential requirements for the development of digital literacy: critical thinking, problem-solving, decision-making, creativity, and innovation (Rahman et al., 2021). Critical thinking, problem-solving, and decision making within the context of digital literacy pointed to the skills of planning and conducting research in order to solve problems and make information-based decisions using the appropriate digital tools and resources (Rahman et al., 2021). It is of the utmost importance that educational pursuits target critical thinking as a key learning outcome in higher education. A study conducted in 1972 by the American Council on Education found that 97 percent of the sampled faculty members believed that the development of critical thinking skills is the most important objective of undergraduate education (Paul, 2004).

While there is widespread recognition of the increasing importance of critical thinking, fashion design education is falling short in acknowledging the industry's intricate connection to broader social and environmental contexts (Postlethwaite et al., 2020). This failure underscores a notable deficiency in the critical thinking skills provided by these fashion design programs. Compounding the issue, fashion design studio courses have stagnated over the past 25 years, failing to adapt to the evolving demands of the fashion industry, which increasingly requires proficiency in advanced manufacturing, digital tools, technology integration, and innovative entrepreneurial models (Postlethwaite et al., 2020). Some strategies have been employed in undergraduate fashion design education to enhance digital literacy and critical thinking, including the generalized integration of technology and improvement of lecturer competence (Sharkova, 2014) but, these strategies have proven to not be effective enough in solving the increasing need for technological competency, especially in the Industry 4.0 era (Chika-James, 2020). While critical thinking skills are recognized as paramount in fashion design education (Faerm, 2012; Russanti et al., 2018), the current state of pedagogy often fails to adequately prioritize their development. Critical thinking ability enables fashion students to succeed in a fast paced, nuanced, and context-oriented industry. In many other industries including math and engineering, 3D simulation software has been shown to encourage the development of critical thinking skills (Suryanti et al., 2020; Syawaludin, et al., 2019).

As the global market transforms, critical thinking and digital literacy should become new focus of undergraduate fashion design pedagogy. To underscore the necessity of these skills in context, one study found that out of all roles in the fashion industry, the careers centered in the initial design and development stage of the product cycle require a greater level of digital competency, based on job advertisements on the largest, fashion-only job listing internet website

(Wang & Brookshire, 2018). As such, it is important to assess whether 3D simulation software, an increasingly marketable design tool, is conducive to students' development of necessary critical thinking skills.

Purpose Statement

This research endeavor intends to observe critical thinking when designing in 3D simulation software, utilizing the relevant tenets of the framework, THREAD. The overall objective centers on shedding light on whether such software fosters critical thinking in the fashion design process. It is pertinent to enlighten the 3D fashion thinking process in a way that might elucidate whether 3D simulation software is conducive to the development of critical thinking skills.

As the fashion industry transforms to meet emerging standards and to integrate new technology, 3D simulation software presents opportunity to improve supply chain process and timeline, ethical and environmental standards, design inclusivity, and knowledge transfer within the organization. Now more than ever, fashion design pedagogy will be required to educate student designers to meet standards of digital literacy, of which a significant component is virtual simulation software. Investigating the role of 3D simulation software on students' development of critical thinking skills and it's positioning in the design thinking and cognitive creation process is increasingly pertinent.

Theoretical Framework

This study employs an emergent theoretical framework of fashion thinking in the virtual design learning environment, THREAD, to ground qualitative protocol analysis. THREAD will ensure coherence in the study's focus and direction, enhancing the rigor and reliability of the protocol. Additionally, utilizing this specific theoretical framework to guide the research method and analysis will contribute to the cumulative knowledge in the field of design cognition, learning in the virtual environment, and fashion design pedagogy.

Paradigmatic Focus on Constructivism

The constructivist paradigm is particularly suitable for grounding this qualitative study due to its emphasis on the active construction of knowledge through interaction with the environment. Verbal protocol analysis captures cognitive processes in real-time, aligning with constructivist ideals by emphasizing learners' active role in knowledge construction. Constructivism can be understood as a paradigm where knowledge is created by the reflexive process of actioning and responding to those actions by creating and adjusting dynamic knowledge structures (Piaget, 1967).

Students in virtual environments exhibit greater independence and agency, fostering proactive learning and critical thinking development (Bose, 2003; Goodyear et al., 2001; Parise, 2000; Smith et al., 2001). Learning apparel design in 3D software mirrors constructivist principles, facilitating self-determination and individualized learning experiences (Boynton, 2002). By situating the study within the constructivist paradigm, it becomes possible to explore how the use of 3D simulation software influences the development and engagement of critical thinking skills among student designers.

THREAD Theoretical Framework

The name "THREAD" for the theoretical framework in this qualitative study reflects a deliberate abstraction of the cognitive processes inherent in the virtual fashion thinking process. The term "THREAD" serves as a metaphorical representation of the interconnectedness and continuity of thought throughout the design process. Just as a thread is woven through fabric, connecting various fibers to form a cohesive whole, the cognitive processes represented by each tenet in the THREAD model thread through the designer's mind. The THREAD framework includes seven tenets of fashion thinking for 3D design pedagogy including: (1) creativity, (2) tacit knowledge, (3) reflexivity, (4) visualization, (5) problem solving, (6) individual agency, and (7) haptic memory. The THREAD framework emphasizes critical thinking as a fundamental aspect of fashion cognition, comprising three essential tenets, which are relevant to this study (Figure 3.1). The tenets utilized in this study include (1) problem-solving, (2) reflexivity, and (3) individual agency. Each critical thinking-specific element of the THREAD framework symbolizes a different aspect of critical thinking, contributing to the overall fabric of fashion thinking.

Problem-solving lies at the core, as designers adeptly navigate technical constraints, budget limitations, and market demands, strategically developing solutions to overcome challenges throughout the design process. Problem solving signifies the iterative nature of design (Oh, 2017). Reflexivity encourages designers to engage in critical self-awareness, examining biases, assumptions, and creative processes to continuously refine their approach (Coorey, 2012). Lastly, individual agency underscores the active role of designers in shaping the fashion landscape, empowering them to make deliberate choices that drive innovation and resonate with consumers. Individual agency emphasizes the personal autonomy and decision-making capacity of the designer (Ennis, 1991). These tenets collectively contribute to a comprehensive model of critical thinking within the THREAD framework of fashion thinking, fostering adaptability, innovation, and strategic decision-making in fashion design. The framework will conceptually ground the analysis of think aloud protocol data.

THREAD aims to abstract out the thread of cognition, highlighting the interconnectedness and continuity of thought that underpins the fashion design process. This abstraction allows us to conceptualize design cognition in a holistic manner, recognizing the intricate web of mental processes that contribute to creative and innovative outcomes in the virtual fashion design learning environment. Utilizing THREAD (Table 3.1) as a conceptual framework will ground the study by offering a system for systematically analyzing the think-aloud protocol by categorizing the data by the seven tenets of fashion thinking in the virtual environment. The model will aid in organization and interpretation of the data while providing a comprehensive model of the complex components of fashion thinking in 3D CLO for fashion design pedagogy. The following is a brief description of each of the three tenets of critical thinking relevant to this study and their application to the disciplinary context.

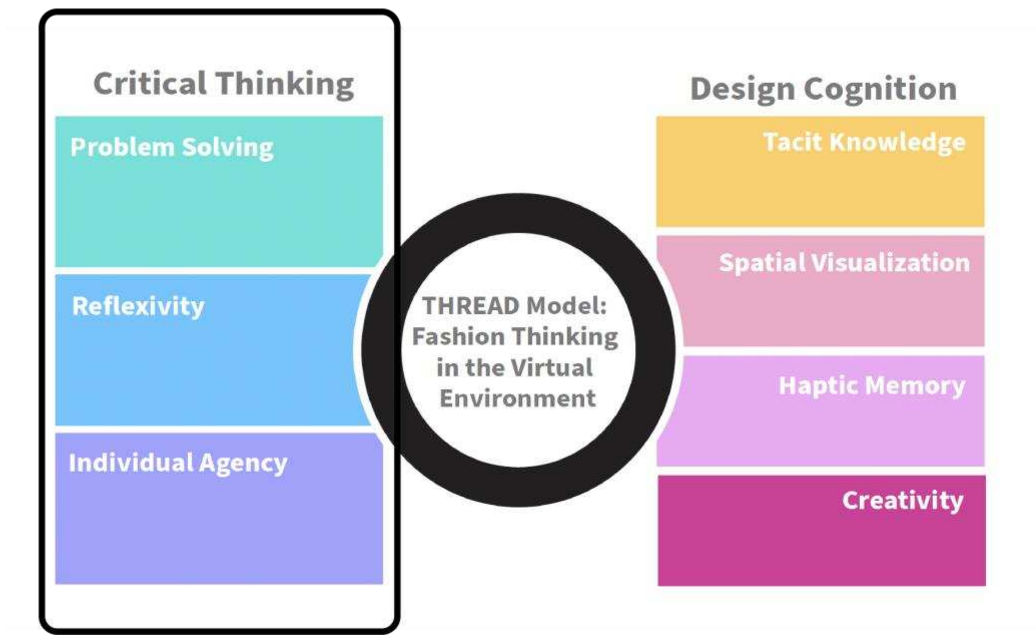


Figure 3.1

Graphic Representation of the THREAD Model (Critical Thinking Focus)

Problem Solving

Problem solving cycles are inherent in the design process, aligning with critical thinking's problem recognition, goal definition, and reflective analysis (Thomke & Fujimoto, 2000; Halpern, 1993). 3D simulation software fosters efficient problem solving by enabling designers to identify issues, modify designs, and assess outcomes in real-time (Fixson & Marion, 2012). Studies have identified teamwork, communication, and problem solving as being three of the most crucial skills for emerging apparel designers (Barrows & Tamblyn; Eilouti, 2006).

Reflexivity

Reflexivity presents a continuous interaction between practitioner and generated material, which is crucial in critical and creative practice (Haseman & Mafe, 2009). Reflexivity enables the transfer of tacit design knowledge and facilitates explicit articulation of knowledge inherent in practice, whether physical or virtual (Schön, 1983; Coorey, 2012).

Individual Agency

Critical thinking involves deciding what to believe or do when creating and assigning meaning to the abstract (Ennis, 1991). Individual agency, integral to critical thinking, embodies proactive pursuit of goals and outcomes, fostering motivation and shaping learning experiences (Chuter, 2020; Pieratt, 2017).

Table 3.1

THREAD Framework of Fashion Thinking for 3D Design Pedagogy

Proposed Tenet	Connection to Critical Thinking	Connection to Fashion Design Pedagogy	Connection to learning 3D simulation software
Problem Solving	Critical thinking requires the crafting of a solution to a problem alongside reflective analysis of the problem (Halpern, 1993).	Product design= sequence of problem-solving cycles (Thomke & Fujimoto, 2000).	Solving problems by building and testing virtual models early in the development process

Proposed Tenet	Connection to Critical Thinking	Connection to Fashion Design Pedagogy	Connection to learning 3D simulation software
Reflexivity	interaction between investigator and research environment (Lamb and Huttlinger, 1989).	design student success: reflection & act of adjusting in the process of creating (Coorey, 2012).	transference of tacit design process knowledge faciliated by reflection
Individual Agency	CT= identify goals and outcomes and to pursue them proactively, purposefully, and effectively (Chuter, 2020).	learned ability to display a growth mindset, grit, and personal ownership over learning (Pieratt, 2017).	students take on a proactive versus reactive role in their knowledge acquisition in virtual environment (Boynton, 2002).

Literature Review

Researchers have found that apparel design and product development students lack critical thinking skills (Fiore et al., 2005). The next section will present an overview of the most important elements comprising the intersection of 3D simulation software, fashion design pedagogy, and critical thinking situated in the broader context of industry 4.0.

With the fashion industry advancing into the fourth industrial revolution, there has been a significant integration of 3D simulation software into the fundamental curriculum of both new and established undergraduate fashion programs. Simulation software is gaining importance in the fashion industry due to the comparatively high costs and time-consuming nature of the traditional method, full-scale physical prototyping (Kunz & Rupe, 1999). Grain found that the newfound efficiencies of 3D design and fitting have resulted in a skillset shortage (2021). In order to fully realize the potential of 3D and to make change in the larger fashion industry, academia must train the designers of the future in 3D software. Despite the emerging relevance of 3D simulation software in the fashion industry, there is a lack of understanding of fashion design learning and cognitive processes in the novel virtual environment. As 3D simulation software has evolved to become an increasingly integrated pedagogical tool for fashion design and an industry staple, it has become imperative that the critical thinking processes specific to the virtual space are articulated.

Exploring whether 3D simulation software enhances critical thinking skills in fashion design pedagogy is crucial because critical thinking is vital to cultivation of students' capacity to navigate the demands of Industry 4.0 (Hafni et al., 2020). Digital literacy competency necessitates a comprehensive skill set rather than a singular skill (Wilson, 1988). Critical thinking significantly influences students' potential and their ability to work with a diverse range of skills (Reding & Newman, 2017). Critical thinking skills enable students to efficiently handle large volumes of information, recognize problems, and pinpoint the best solutions, all skills essential for effectively navigating and utilizing 3D simulation software in fashion design.

Critical Thinking

Critical thinking, as we understand it today, originated in the mid-late 20th century in the United States. However, its roots can be traced back 2500 years to ancient Greece, where the Socratic method was first developed (Eskelinen, 2019). The term, “critical” originates from the Greek word, “Kritikos”, denoting the ability to authorize, discern, or decide (Padmanabha, 2018).

John Dewey, an American philosopher, psychologist, and educator, is often considered the pioneer of modern critical thinking. He argued that practicing reflective thinking involves not only organizing ideas in the mind, but also establishing a coherent sequence to determining subsequent steps and outcome (Dewew, 1933). Dewey viewed focused reflection as a complex and purposeful thought process leading to learning from experience (Dewey, 1933). Fashion designers employ an iterative process, continuously reflecting on and refining their designs.

There is a somewhat divided view of the context of critical thinking; some believe that critical thinking instruction is best taught as an integrated element in a specific subject matter whereas others purport that critical thinking acumen is a generalized set of skills to be taught separately from contextual subject matter (Ennis, 1993). In the sphere of teaching and learning, Ennis's work on critical thinking is regarded as exceptionally relevant. He defines critical thinking simply as, "focused on deciding what to believe or do" (Ennis, 1993, p. 8). Adult students who engage critical thinking skills have been found to approach coursework in a thoughtful and reflective manner, ask challenging questions, and be more immersed in the learning process and later, they have been found to activate critical thinking skills in the workplace (Murawski, 2014).

Critical Thinking in Fashion Design

Critical thinking is a skill that can be taught and therefore, perhaps it is not a natural outcome of college coursework, regardless of discipline. As adult education shifts to accommodate the technological advancements of the fourth industrial revolution, where software and information are defined by change and speed, critical thinking skills are imperative for both academic and industrial success. "Knowledge is not enough. The creative, constructive, design and operating aspects of thinking are just as important as knowledge" (Debono, 2004, p. 6). Fashion design is shifting to mirror this paradigmatic transformation.

Critical thinking stands as a pivotal skill essential for successful fashion design across both academic and industrial landscapes as the paradigm shifts to meet the demands of Industry 4.0 (Benešová, 2017; Cabrita et al., 2020). Critical thinking is paramount in fashion design education as it equips designers with the skills necessary to navigate the complexities of the industry, foster innovation, make informed decisions, understand consumer needs, address sustainability concerns, and effectively communicate a design vision in an ever-evolving global market (Kozar & Connell, 2015). Critical thinking is vital for fashion designers in Industry 4.0 because it provides them with the essential tools to thrive in the multifaceted landscape of the industry.

Industry 4.0

Launched by the adaptation and expansion of consumer trends, a myriad of technological improvements have led to the fourth industrial revolution, Industry 4.0. The first industrial revolution centered on production by way of steam and waterpower; Industry 2.0 was characterized by the invention of electricity; Industry 3.0 refers to the emergence of electronics and information technology; and the fourth industrial revolution is now characterized by the movement into cloud computing, digitization, simulation, and the resulting automation that is achieved through the human-machine interaction (Hermann et al., 2016). The fashion industry plays a significant role in the global market and has experienced foundational technological change as it adapts to Industry 4.0. 3D simulation software is at the forefront of the future of this change, offering automated solutions for product design, development, and production.

As Industry 4.0 is characterized by the integration of digital technology, automation, AI, and the Internet of Things (IoT) into manufacturing, production, and the overarching supply chain, critical thinking will be required to adapt as new technologies including 3D simulation software influence how we conceptualize, design, and manufacture fashion. It is known that Industry 4.0 will require rapid innovation cycles (Schuh et al., 2018). Industry 4.0 has propelled the global market into a new age centered on automation and data transmission, propelling many different industries into greater operational efficiency in terms of time, cost, and overall productivity (Erboz, 2017). 3D simulation software has been instrumental in improving industry product development performance in terms of cost reduction, efficiency, and even sustainability.

It is imperative that fashion academia mirrors the needs of industry by producing designers with the skills, abilities, and competencies central to the virtual environment. Within the framework for 21st Century Learning, digital intelligence is of the utmost importance (British Columbia Digital Literacy Framework, 2019). Digital intelligence is the ability to navigate the digital environment including media, software, and technology (The Partnership for 21st Learning, 2017). As Industry 4.0 increases the use of software and digital analytics in the fashion industry, the demand of software skills and information technology expertise in the workforce mirrors this change (Rübmann et al., 2015).

3D Simulation Software

In a general sense, 3D simulation software, which is also known as 3D visualization, 3D modeling, and virtual prototyping, centers on the creation and manipulation of objects with geometric shapes and physical properties and behaviors in the virtual environment (Cai et al., 2013). The manipulatable shapes are comprised of meshes, which are essentially polygons of particles, that can be edited to specifically mimic different materials and their corresponding drape and physical appearance. Researchers in a wide range of disciplines including physics, mathematics, chemistry, civil engineering, and material science, have found that 3D simulation software has been shown to encourage the development of critical thinking skills (Suryanti et al., 2020; Syawaludin et al., 2019; Tercete et al., 2017; Astuti et al., 2020).

Ushered in by Industry 4.0, the incorporation of sophisticated, low-cost 3D software in the product design and development process presents new opportunity for learning and innovation in design (Thomke & Fujimoto, 2000). 3D offers an expansive platform to enable new forms of knowledge creation and execution by encouraging product solution exploration (Becker et al., 2005). 3D kickstarts the problem-solving process through iterative product cycles, leading to organizational improvement from an industry standpoint (Fixson & Marion, 2012).

Industry Applications of 3D Simulation Software

At the crux of wins facilitated by 3D simulation is the ability to greatly reduce lead times not only in the design component of the product development lifecycle but also in merchandising and materials development. 3D simulation software has had a direct effect on the materials buying process, giving developers the ability to view and interact with the drape, hand, luster, and other properties of a fabric in the virtual environment before purchasing a physical sample (D'Apuzzo, 2007). The different characteristics of a textile are present in each piece of rendered material, and all are completely editable. Additionally, many companies are exploring the use of 3D renders on internet shopping platforms to represent their apparel offerings, in lieu of or in addition to photography (D'Apuzzo, 2007).

Fit Renaissance

3D body scanning and 3D simulation software has also produced a fit revival, as accurate body measurement data is imperative for successful fit and overall design (Mitchell, 2021). 3D simulation software has the capability to be seamlessly connected to virtual body scanners where measurements from the scanners can be created into 3D simulation software-compatible avatars for virtual fittings. The avatars generated by the interplay of 3D scanners and 3D simulation software are precise and accurate to a level that is truly revolutionary. Virtual body scanners support sustainable initiative through the improvement of sell-through and the reduction of general cost and waste resulting from online returns (Mitchell, 2021). As such, 3D systems have recently been referred to as, ‘The Door to the New Virtual World’ (Leyer et al., 2019). By improving overall fit and design efficacy, 3D systems have supported sustainable strategies that center on designing long-lasting, quality garments.

Sustainability

According to Seigel (2011), consumer demand is now four times higher than in 1980 and the rate of industry production has followed suit, mirroring the rapid pace of demand. Due to this upward trajectory in apparel consumption, production, and disposal, the fashion design discipline is no longer driven by need (Van der Velden & Vogtländer, 2017). To remedy our fast fashion and global consumption problem, the industry needs designers equipped with 3D technology skills that reduce prototype waste, enact virtual sample adjustments, and make zero-waste design more feasible. According to McQuillan (2020), 3D patternmaking and design software will play a critical role in changing the fashion industry’s outlook on sustainability through zero-waste fashion design techniques, 2D pattern-cutting, waste reduction, and the exploration of new design workflows. 3D simulation software facilitates a hybrid approach where design, technical design, product development, and patternmaking synchronize to achieve zero-waste outcomes. Additionally, virtual fit sessions aid in visualization of pattern modifications instantly, reducing product development time, cost, and waste (Park et al., 2010). In fact, when compared to physical prototyping, digital fashion sampling was found to reduce carbon footprint of up to 30% (Xiong, 2020). Another study found that virtual prototyping reduces carbon-dioxide emissions by 97% and saves 3,300 liters of water (Dressx, 2020). Driven by opportunity to improve sustainable practice and overall workflow compounded by the need for pedagogy centered on digital literacy, it is necessary to investigate and identify critical thinking skill development when designing into 3D simulation software.

Design Inclusivity

Mirroring the changes of growing technologies and the shift towards a globalized garment industry, fashion designers' approach to product creation has become more user-centered, with a need for genuine involvement and empathy for the ultimate consumer (D'Andrea & Teli, 2010). The introduction of 3D simulation software has kickstarted a revolution in the way garments are produced. With anthropometric measurement solutions such as the translation of body-scan data into 3D avatars combined with virtual visualization of design outcome, garments can be custom-built to fit a consumer and then confirmed before production of the physical item (D'Apuzzo, 2007). For example, Dressarte Paris uses 3D simulation software in bespoke tailoring services to incorporate virtual measurements of a customer's body in order to produce a customized avatar for customized couture garments.

Mass Customization. One of the many design approaches that has been improved by 3D simulation software is rapid prototyping, which reflects a market need for product customization and personalization (Delamore, 2004). 3D simulation software enables made-to-measure garment alteration, where 2D patterns can be altered based on visual analysis of 3D simulation, resulting in custom fitting and sampling in the virtual environment (Apeagyei, 2010). In this way, garment prototypes can be tested quickly for size-specific target markets and size systems and grading can be subsequently assessed and improved (Ashdown et al., 2004). 3D for mass customization presents a unique opportunity for the inclusive fashion space, reducing barriers to equality in merchandising offerings for consumers of all body types. One study found that 3D body scanning mobile applications improve fit selection and enhance the methodology for clothing production to become more aligned with mass customization (Idrees et al., 2021).

While mobile 3D scanners have a different operating system from 3D simulation software for fashion design, mobile 3D scanners are compatible with simulation software. 3D scanners, with the help of simulation software, make mass customization and the resulting forward trajectory of inclusive fashion possible through the use of digital body dimension data. With the creation and application in simulation of avatars based on real human measurements, the aspirational outcome will be a contactless and user-friendly method of obtaining personalized fit, regardless of body shape or size.

Traditional dress forms and croquis templates that are used in the industry have an hourglass shape and assume a direct proportion between the bust, hips, and waist (Boorady, 2014). Design in the commercial market typically follows the standard women's size 8 body proportions, which does not align with that of all people. "While ideals may be useful, simplifying our view of the world and in some ways making design more efficient, relying on ideal forms may lead to missed opportunities: Human needs that could be addressed with products designed for real human bodies" (LaBat & Ryan, 2019, p. 9). As Brownbridge, Sanderson, and Gill explain, "Fashion design is the first process for garment construction and dictates the proportion of the garment" (2016, p. 1). As designers are following the standard size 8 measurements for all design, "the process becomes compromised, leading to fit issues and dissatisfied customers" (Brownbridge et al., 2016, p. 1). This problem can be somewhat mitigated with the use of 3D simulation software acting as the means of communication between designer, consumer, and manufacturer.

Mass customization would be a beneficial step towards inclusive apparel design and development, and customization must start from a garment pattern that is correctly shaped for the corresponding population. According to Zakaria and Ruznan (2020), "When body shapes and sizes are analyzed and understood, then the development of the right size clothing for good fitting garments can be achieved" (p. 91). The improvement of communication from the designer to the manufacturer can be accomplished with the incorporation of 3D simulation software. 3D avatars that exactly match the dimensions of the target consumer manifests in better fitting and more comfortable garments for the target population. The design of garments using 3D simulation software mirrors the cultural values of the time, allowing for a more inclusive and democratic approach to fashion because each garment can be personalized and fit to any body shape or size. In this way, 3D simulation software is effective in streamlining the production process at the design and development stages of the supply chain cycle.

Supply Chain

The supply chain of the fashion industry is comprised of 9 main stages: (1) merchandising and market research on trends and direction; (2) creative conceptual design followed by technical design comprised of croquis and 2D CAD sketches; (3) product development process and analysis; (4) prototyping; (5) line reviews and line presentation to buyers; (6) manufacturing by production team/factory; (7) marketing endeavor for retail space; (8) distribution through operations teams; (9) retail of garments to consumer through in-store, on-line, or other retail channels (Casciani et al., 2022). 3D simulation software fundamentally changes the supply chain in the first 4 steps. First, virtual prototyping cuts lead time from a few weeks to a couple of days. Hybrid teams emerge as cross-departmental collaboration is made more streamlined through a faster means of visual communication between designers, patternmakers, and product developers (Casciani et al., 2022). 3D simulation software creates space for an integrated design and development strategy, integrating prototyping, fit tests, functional performance simulation (thermal mapping), visualization of aesthetics (silhouette, graphics, print, color, fabrication), and manufacturing specifications (Papachristou & Bilalis, 2015). Many production industries have adjusted their production strategy to center more on customization and reduction in lead time (Brettel et al., 2014). 3D simulation software is already impacting the supply chain by disrupting the traditional prototyping and manufacturing process, rerouting much of the design and product development process from offshore to domestic production, underscoring sustainability impact (Winnan, 2013).

The industrial benefits of 3D simulation software including an improvement in size and fit, revolutionary sustainability opportunity, inclusivity initiatives, and supply chain optimization underscore the likelihood that 3D simulation software will be an increasingly indispensable tool in the fashion industry. Industry demand will perpetuate a need for fashion design graduates with progressively advanced skillsets in digital literacy and 3D programs. From a pedagogical angle, it is important to investigate whether 3D simulation software is conducive to the development of critical thinking skills. In this way, fashion design academia can begin to investigate the methods needed to prepare the future designers of Industry 4.0.

Critical Thinking in Industry 4.0

With Industry 4.0, virtual products and systems are becoming more complex and interconnected, resulting in the need for apparel designers to comprehend not only the individual software programs but the role they play in the larger design process. Modern product design requires increasingly innovative solutions, underscoring the need for an understanding of the cognitive learning processes at the root of design thinking to foster innovation. In essence, studying design cognition in the context of Industry 4.0 is pertinent for empowering future designers with the cognitive skills, strategies, and insights needed to leverage technology effectively. In order to best prepare student designers to enter the ever-changing contemporary fashion industry, we must arm them with the ability to foster innovation, adapt to change, and produce human-centric, sustainable, and competitive designs. To do so, it is crucial to understand critical thinking in the virtual environment.

Adaptation to Technological Advancement

The ever-changing fashion industry and textile landscape is being continuously updated by technology. Driven by increasing competition and consumer appetite, 3D technology has been adopted at a rapid pace in order to aid the production process, eliminate inefficiency, and streamline supply chain (Choi, 2022; Hodges et al., 2020). Virtual technology and 3D simulation software is becoming an industry standard and as such, fashion design graduates will soon be required to possess the corresponding skillset that enables utilization of the emerging software to optimize efficiency, promote inclusivity, reduce cost, and mitigate waste (Conlon & Gallery, 2023). As the fashion industry becomes increasingly reliant on 3D simulation software and AI-driven analytics, critical thinking helps designers adapt to these changes and leverage new tools in the process.

Digital Literacy

Critical thinking is arguably an integral component of digital literacy, as it equips learners with the skills necessary to navigate, analyze, and evaluate digital software, technology, and the virtual world. Integrating the essential skills of critical thinking and digital literacy could be “a set of skills and practices” (Avila & Pandya, 2013, p.2), a type of curatorship (Potter, 2012), or content-shaping (Jenkins, 2008). One study found that digital literacy skills contribute to overall critical thinking, indicating a need for educators to incorporate digital literacy into instruction (Amin et al., 2023). Despite the connectivity of digital literacy skills to critical thinking, it has been purported that students lack digital literacy as an outcome of their fashion design education, particularly in using computer aided design software and technology to actualize collections (Ernawati, Hidayat, Primandari, Ferdian, & Fitria, 2022). Competence in digital literacy can be enhanced in undergraduate fashion design education through integration of technology in the pedagogical curriculum (Sharkova, 2014). Specifically, studies show that digital literacy of undergraduate fashion design students is improved when they engage in industry-led projects which center on the process of designing, creating basic patterns, and engaging in design thinking through technology (Ryan, 2020).

Understanding Consumer Need

Critical thinking permits designers to analyze and understand the diverse needs, preferences, and behaviors of the target consumer. The surge in consumer demand, which has witnessed a staggering fourfold increase since 1980, has exerted immense pressure on the fashion industry to ramp up production and offer increasingly personalized product choices (Seigel, 2011). In response to this evolving consumer landscape, fashion designers are compelled to embrace a user-centered approach, as advocated by D'Andrea and Teli (2010), wherein garments are meticulously customized to cater to the specific needs of the consumer even before the commencement of physical production. Critical thinking skills serve as the cornerstone of this user-centered design philosophy, facilitating a multifaceted analysis of consumer data, market trends, and cultural influences (Lawson, 2005). By employing critical thinking, designers focus their attention on research and meeting users' needs and desires (Watkins & Dunne, 2015; Nixon & Blakley, 2012). Through critical analysis and evaluation, designers can anticipate consumer needs with precision, fostering the development of innovative solutions; Leveraging Industry 4.0 software enhances this process by improving precision, speed, and accuracy in interpreting vast amounts of consumer data (Sun & Zhao, 2018). Additionally, fashion thinking, which necessitates, critical thinking, fosters empathy, allowing designers to adopt a user-centric perspective and develop products that authentically resonate with the emotions and experiences of the consumers (Nixon & Blakley, 2012). In essence, critical thinking skills are indispensable in the realm of fashion design, serving as a guiding force in crafting products that not only meet but exceed the ever-evolving expectations of the modern consumer landscape.

Sustainability and Ethical Considerations

Fashion designers are expected to consider sustainability and ethical practices when designing collections. Critical thinking skills enable them to assess the impact of their choices, addressing the issues of fast fashion and global consumption. Critical thinking skills will be the driving force in designers' ability to reduce prototype waste, enable virtual adjustments to samples, and advance the zero-waste design initiative (McQuilllan, 2020). A few authors have suggested that adopting a viewpoint defined by critical thinking is crucial for enhancing sustainability in fashion, particularly through innovative approaches like divergent 3D design thinking (Black 2012; Meyer 2015; Shine et al., 2016; Sun & Lu, 2015; Weller et al., 2015; White et al., 2015). By considering factors such as philosophy, materials, and equipment selection, this approach can pave the way for new narratives surrounding 3D printing and zero-waste fashion, ultimately contributing to more sustainable practices in the industry (Pasricha & Greeninger, 2018).

Continuous Learning and Adaptability

Fashion is a field that demands continuous learning and adaptation in order to stay relevant. Critical thinking encourages a mindset of lifelong learning, embracing new ideas, exploring diverse perspectives, and adaptability to change. One study found that there is a positive correlation between lifelong learning and critical thinking skills (Deveci & Ayish, 2017). Green purports that the most impactful way to teach critical thinking is through encouraging students to develop their ability to think critically even when their formal schooling has ended, by providing them with the tools to be a lifelong learner (2015). The key characteristic of lifelong learning is taking responsibility for learning by initiating and sustaining the learning process independently (London, 2011).

3D Simulation Software and Critical Thinking

The incorporation of 3D simulation software in the undergraduate fashion design classroom is central to developing the foundational knowledge at the apex of critical thinking. It has been found that the use of simulation technology in the classroom heightens students' critical thinking abilities in many disciplines. Fostering student ability to divulge in exploratory, action-oriented, and transformative learning, such as can be gleaned through 3D simulation pedagogy, encourages development of the ability to think critically and systematically (Terkildsen et al., 2020). For example, Yu (2018) contributes to the knowledge of teaching simulation software in fashion pedagogy by researching student acceptance and usage of the programs in fashion merchandising.

Yu (2018) found that technology-integrated activities using 3D simulation software in fashion merchandising courses enables students in their development of critical thinking skills. Through a Pearson correlation, Yu (2018) found that students who perceived simulation software technology in the merchandising classroom to be useful, easy to use, and enjoyable were more likely to also perceive improvements in critical thinking after using the simulation software technology. Additionally, it was found that students who show a more positive attitude towards the use of 3D design software are more likely to improve critical thinking skills when compared with those who show a less positive attitude towards the use of technology. One can infer from this finding that the pedagogical methods employed to teach 3D simulation software are of critical importance in student acceptance, and therefore, students' ability to develop their critical thinking skillset. "Without pedagogy, an interactive [3D] environment will never be a learning environment" (Cai et al., 2013, p.11). Justified by Industry 4.0 and its growing digital literacy requirements, observing critical thinking within the environment created by 3D simulation software will begin a discourse on the role of virtual technology on education and skill development for undergraduate fashion design pedagogy.

Methodology

This study aims to explore critical thinking situated within the environment facilitated by 3D simulation software, leveraging three tenets of critical thinking within the innovative THREAD framework, among student designers. This research seeks to elucidate critical thinking within the virtual fashion design process. The following research question aims to elucidate the purpose: How does the virtual environment produced by 3D simulation software engage critical thinking skills in the fashion design process? In order to investigate critical thinking in the 3D fashion design process, verbal protocol data was aligned with the relevant tenets of the THREAD model.

Qualitative methodology was deemed to be well-suited for this study because qualitative methods allow for in-depth exploration and understanding of participants' experiences, perceptions, and behaviors, which is essential for examining complex phenomena such as critical thinking in a design context. Verbal protocol analysis and screen recordings provided rich, detailed data that captured participants' thoughts and actions as they engaged with CLO, offering insights into their cognitive processes and decision-making strategies. Additionally, qualitative research allows for flexibility and adaptability in data collection and analysis, enabling the exploration of emergent themes and patterns in the data. This approach aligns well with the dynamic and iterative nature of design processes, where creativity and problem-solving skills are central.

Study Design

The methods design centered on the aim for more in-depth exploration of participants' critical thought processes in real-time. The verbal protocols captured participants' cognition as they engaged in virtual design of their collection, providing insights into immediate reactions, decision-making, and problem-solving strategies. In engineering design thinking research, protocol analysis has been employed to assess designers' display of creativity (Toh & Miller, 2016; Gero et al., 2019; Maher et al., 2017), the role of sketches (Bao et al., 2018; Bilda et al., 2006), and cognitive patterns when engaging in an engineering design task (Kavakli & Gero, 2002).

When looking at the historical and successful utility of the think aloud protocol in engineering studies (Kavakli & Gero, 2002), its application translates also to a study assessing fashion design students' critical thinking when utilizing 3D simulation software. Protocol methodology is well established in engineering studies for uncovering the thought processes (Atman et al., 2005) and decision-making (McComb et al., 2015; McComb et al., 2017) involved in design thinking. Similarly, in fashion design, understanding how designers' approach and navigate the design process is crucial for assessing critical thinking skills.

This study can be categorized within human centered interaction (HCI) research, which centers on the interface between people and computers. In HCI practice, the think-aloud protocol, which is often referred to as the usability method, is the single most frequently applied technique (Clemmensen, 2002). By utilizing verbal protocol, "you will be able to detect cognitive activities that may not be visible at all" (Hackos & Redish, 1998, p.259). Verbal protocol analysis detects tacit cognitive processes, such as critical thinking.

Study Environment

The environment for this study was 2 senior undergraduate fashion design capsule courses where CLO 3D was a method of design required for the final outcome. Capsule in this context means that the courses centered on a mini project or final collection. In both courses, the researcher was the instructor. The first course was entitled Technical Studio III and focused on 2D and 3D iterations, the digital sampling process, and the use of 3D simulation software (CLO) to ideate, draft patterns, drape, fit, and present final design collections. The second course, Senior Thesis Collection, centered on the actualization of senior fashion design students' capsule collections, which were required to be presented in 3D form.

Before beginning these courses, students had already completed projects and modules in 3D CLO in prerequisite courses that demonstrated their competence in the software. The courses sampled were offered once a year in the fall term (both A and B sections) and the structure required that students entered the class with existing proficiency at an intermediate level in 3D simulation software in order to successfully actualize 3D renders of their designed garments in a final capsule collection project. The courses were required for fashion design students' completion of their degree program, and both were comprised of junior and senior students.

The researcher classified and estimated participants' comfort levels, expertise levels, and years of experience in CLO 3D based on multiple factors, including their previous work in CLO 3D within the two courses sampled, their academic standing and course progression at the college, and their perceived familiarity and confidence with the software during data collection.

The 1-5 comfort level ratings were determined based on a combination of students' perceived confidence in CLO 3D, their observed proficiency in coursework, and the complexity of tasks they were able to execute independently. A rating of 1 indicated minimal comfort with the software, while 5 represented a high degree of ease and fluency in navigating CLO 3D for advanced tasks such as virtual draping, pattern manipulation, and rendering. Students who demonstrated strong command of CLO 3D tools, worked efficiently with little instructor guidance, and expressed high confidence in their abilities were rated at the higher end of the scale (4-5). Those who required more troubleshooting or expressed hesitancy in executing complex tasks were rated lower (2-3).

The beginner, intermediate, and advanced expertise levels were assigned based on a combination of students' years of experience and their demonstrated ability to handle CLO 3D functions at increasing levels of complexity. Given that all students in these courses had completed prerequisite CLO 3D coursework, none were classified as beginners. Instead, intermediate students were those who had 1-2 years of experience and demonstrated competence in fundamental CLO 3D functions (e.g., basic pattern manipulation, garment construction, and simulation). Advanced students had either 3+ years of experience or exhibited strong technical proficiency in executing complex tasks such as multi-layered garment simulations, advanced material applications, and integrating CLO 3D into their broader design workflows with minimal guidance.

Since enrollment in these upper-level courses required prior successful completion of prerequisite CLO 3D projects and modules, all students were expected to have at least an intermediate level of proficiency before beginning the course. However, individual comfort levels still varied, ranging from 3 (moderately comfortable) to 5 (very comfortable), as shown in Table 3.2. Demographic data was not collected.

It was logical to conduct a study exploring 3D simulation software and student designers' critical thinking processes within the context of upper-class undergraduate fashion courses for several reasons. Firstly, the course structure, which required that students entering the course already had an intermediate understanding and ability in 3D, provided a conducive environment for studying the software's influence on critical thinking. Additionally, the course's emphasis on the creation of a collection (senior capstone or capsule) project highlighted the practical relevance of the study, as these are activities that closely mirror real-world design scenarios. Moreover, the courses' statuses as foundational for junior and senior fashion design students underscored the importance of understanding the interaction between 3D simulation software and critical thinking, as it directly relates to students' preparation for their future careers in the fashion industry.

Table 3.2

Participants' Comfort Level, Expertise, and Experience in CLO 3D

Student ID	Comfort Level (1-5)	Expertise Level	Years of Experience with CLO 3D
S1	4	Intermediate	1-2 years
S2	4	Intermediate	1-2 years
S3	3	Intermediate	1-2 years
S4	4	Intermediate	2 years
S5	3	Intermediate	1-2 years
S6	5	Advanced	3+ years
S7	5	Advanced	1-2 years

Student ID	Comfort Level (1-5)	Expertise Level	Years of Experience with CLO 3D
S8	3	Intermediate	1 year
S9	4	Intermediate	1-2 years

CLO 3D

CLO 3D is a 3D simulation software program. 3D simulation software in fashion design centers on providing a platform where the user can pattern-make, design, and render virtual garment prototypes. Essentially, virtual means digital, which denotes that the process is occurring on a computer or computer network (Mitra, 2003). The software enables the designer to prototype all angles and details of the virtual garment and to even render out photorealistic imagery that can be seamlessly incorporated in tech packs, product line management systems, and even as online representations of product. 3D simulation software provides a singular environment for patternmakers to draft the patterns, stitch them together in the corresponding 2D window and then position the pattern pieces correctly around 3D avatars for the eventual simulation of the garment on the form, producing a high-resolution image referred to as a render (Baytar, 2018). With 3D CLO, designers can create virtual garments with remarkable realism, allowing for detailed visualization and manipulation of fabric drape, texture, and fit. The software enables seamless transition from initial concept to final product, streamlining the entire design process.

Participants

The study adopted a convenience sampling approach, where all interested participants from two classes comprising a total of 17 students were included in the study (Wienclaw, 2019).. The interested participants totaled 9 and this was enough to reach saturation. The convenience sample, which is the most common sampling method employed in qualitative research, is defined as the collection of data from whoever is willing to participate in a study, is the most approachable, or the most conveniently accessible to the researcher (Wienclaw, 2019). Participants were recruited through a portal e-mail letter administered to all students in each course by the instructor. All students were granted 10 points extra credit for participation in the think-aloud protocol. An alternative activity was created and managed by the instructor of the course for students who still wished for extra credit but did not want to participate in the study. The sample was 9 students who were interested in participating from a group of 17 in two upper-class courses involving 3D simulation software situated in a fashion design department within a Western 4-year college. Selection criteria included having taken 1) all required prerequisites for the course sampled, which demonstrated adequate proficiency and experience in the software, 2) at least three years of training in hands-on patternmaking, apparel construction, and/or sewing, and 3) experience in application of 3D simulation software knowledge to final product development or rapid prototyping. The course prerequisites and structure ensured that all selection criteria was met simply by being a student in the course, hence the convenience sampling approach.

Conversely, exclusion criteria involved inexperience with 3D software. Demographic details included: 1) fashion design specific degree specialization, 2) final two-year stage academic degree progression, 4) technological proficiency, and 5) interest in fashion design and 3D technology to ensure a comprehensive participant pool. The demographics listed aligned with the course sampled as the class included junior and senior level fashion design students with a background of coursework in 3D simulation software and patternmaking, with the same proficiency in 3D software considering the academic stage of progression. The selection process described aimed to ensure that participants possessed the requisite background and expertise to offer valuable insights into critical thinking within the virtual environment. With all interested participants included in the study, the research questions were effectively explored, and the data collected from 9 students reached saturation.

Data Collection

The methods plan centered on screen recordings and think-aloud protocol, where students' critical thinking processes were captured as they worked through their collection in 3D CLO.

Think-Aloud Protocol

The think-aloud protocol was chosen because it provided an intimate and real-time perspective on the mechanisms of students' critical thinking processes as they worked within the 3D CLO environment (Atman and Bursic, 1998). By verbalizing their thoughts while actively engaging with design tasks, participants revealed their decision-making strategies, the ways they evaluated feedback, and how they connected specific design choices to broader principles. This method allowed for immediate access to their critical thinking processes, offering valuable insights into how students analyzed, reflected, and iteratively solved problems while using 3D tools.

In contrast to design cognition—which involves tacit, intuitive, and often unspoken knowledge—critical thinking is more readily observable, encompassing processes such as problem-solving, reflexivity, and decision-making using agency. This distinction made the think-aloud protocol particularly appropriate for studying critical thinking, as it enabled the researcher to "see" participants' analytical and reflective engagement in real time. By capturing how students evaluated options, responded to software feedback, and adapted their approaches, the think-aloud protocol aligned well with the process-oriented and explicit nature of critical thinking, making it an effective method for investigating this dimension of THREAD.

In the literature, thinking aloud goes by various names such as verbal reports, concurrent verbal protocols, retrospective verbal protocols, after think-aloud, and verbal protocols (Nielsen et al., 2002). Regardless of its nomenclature, a think-aloud protocol is a research methodology that requires one or more participants to verbalize their thoughts as they work through a design problem (Ericsson & Simon, 1993). Think-aloud protocols emerged as a methodology for elucidating human cognition in the field of cognitive psychology (Cooke, 2010). It has been purported that think-aloud protocols are the most effective known methodology of garnering a reflection of the cognitive processes of individuals in their natural state (Ericsson & Simon, 1993). Nisbett and Wilson conducted a review study that postulated that participants' reports on their cognitive processes in think aloud protocols are accurate, especially when the stimuli is salient and plausible (1977). Verbal protocols have been successfully employed in the following contexts: (a) to demonstrate participants' ability to transfer problem-solving knowledge from previously encountered challenges to new solutions (Ross, 1984), (b) to study participant cognition when engaged in expert chess strategy in the 1940s (van Someren et al., 1994), and (c) to elucidate general cognition.

The think-aloud protocol is highly regarded in cognitive research due to its less structured nature, which enables participants to use their own language and natural dialogue (van Someren et al., 1994). In this way, the risk of researcher imposition on cognition when designing is mitigated, which is critical for collecting think-aloud data with student designers. Design thinking is inherently difficult to capture, due to its tacit nature. It has been shown that the study of design drawings alone does not offer much insight into cognition as the researcher focuses on the designed product or outcome, and not the process itself (Atman & Bursic, 1998).

Think-Aloud Protocol in Design

The think-aloud protocol method focuses on capturing participants' thought processes and problem-solving strategies during the design process rather than solely on the final product. This approach is advantageous because it provides insights into the cognitive aspects of design, such as decision-making, creative problem-solving, and critical thinking, which are often overlooked when solely examining the end result. By centering on the design process, researchers can gain a deeper understanding of how designers approach challenges, make decisions, and iterate on their ideas. Utilizing think-aloud protocol for data collection in design research offered direct insight into participants' real-time thought processes, allowing for the study of critical thinking and problem-solving strategies in the complex virtual environment.

Dorst and Cross (2001) observed that designers move between problem space and solution space during the design process, with the problem space focusing on understanding the task at hand. In think-aloud sessions, participants engage in the problem space by analyzing the task, identifying constraints, and seeking clarity on the assigned problem (Cross & Dorst, 1999). Understanding designers' cognitive processes requires studying them as they work through design tasks. Donovan et al. (1999) found that allowing designers to verbalize their thoughts enables them to articulate their conceptual understanding and draw from past experiences. Atman and Bursic (1998) advocate for using verbal protocol analysis to assess students' problem-solving skills in engineering design education. They suggest employing think-aloud protocols to evaluate students' approaches to solving open-ended design problems. This study drew on literature to justify the use of cognitive task analysis and outlined procedures for conducting think-aloud sessions with elementary school students. For instance, van Someren et al. (1994) propose think-aloud protocols as a more natural method for capturing young designers' thoughts compared to direct elicitation techniques. The traditional thinking aloud technique by Ericsson and Simon is often adapted and adjusted for new contexts and applications (Boren and Ramey, 2000), underscoring its applicability to new domains such as critical thinking for 3D simulation software in fashion design.

In order to elucidate critical thinking in this study, the think-aloud protocol involved the recording of students' screens and voices as they talked through the design and development of their capsule collection project in 3D CLO. The participant observation took place virtually, where screen-recordings were taken by capturing participants' video and audio on their personal machines as they worked through translating, talking through, and conceptualizing their final designs in the 3D space. The first step in actualizing the methods of this study was a meeting with the principal investigator (PI) and the participants who confirmed interest. The PI explained the research and think-aloud protocol procedures with a demonstration. Participants were provided with clear instructions on the think-aloud process, underscoring their role in vocalizing their cognition, describing problem and solution finding, and expressing any uncertainties or challenges they encounter while designing. The researcher emphasized to students a focus on the "why" or "because" in their protocol, underscoring the reasoning behind actions, not just the actions themselves. The researcher encouraged that students visit other sites if they needed to look up instructions and how-to videos during their protocol session, as this was important to document as a component of the critical thinking process. Students were encouraged, but not required, to speak continuously during the time their screen was recording, with a focus on describing their actions, reflections, and any design considerations. Screen recording software

(Quicktime on Mac and ShareX on PC) was employed as participants worked on their personal machines and recorded all video and audio data. The students had already received the license for log-in on 3D CLO software, including the username and password as a course requirement.

The time students were encouraged to spend engaged in the recorded design task was around 60 minutes, with room for extension or reduction if necessary and most students remained in this ballpark range with some as low as 36 minutes and others as high as an hour and 20 minutes, with some students submitting multiple protocols. All protocols were analyzed regardless of time. The general time limit was suggested to students for the think-aloud protocol because without a designated design activity with a natural endpoint, a time limit helped create structure and focus, creating an organic capture of a moment in time in the designer's process. Since the study aimed to observe critical thinking within the context of organic design using 3D simulation software, a time limit ensured that participants' cognitive processes were captured with some reference to time, simulating a realistic design scenario. This approach allowed the researcher to observe how participants prioritize and engage in critical thinking throughout the design process, even in the absence of a predetermined endpoint for the task. The protocols were combed for the most pertinent content during data collection. During collection of protocol data, the researcher took on the role of complete observation, without interference in the design event. A digital journal was held when reviewing the screen recordings to begin to make some preliminarily assumptions about the students' learning processes.

Pilot Protocol

A pilot of the think-aloud methodology was enacted with a recent graduate who is very familiar with 3D CLO and utilizes the software as a component of her position at a Fortune 500 fashion company. This candidate was chosen because as a recent graduate, she had experience using 3D simulation software in both her academic and professional experience. This made her a uniquely suitable candidate to provide valuable insight and feedback on the think-aloud protocol's effectiveness and comprehension. The pilot permitted the identification of potential flaws and ambiguities in the protocol's instructions and procedures before conducting the main study. This ensured that the protocol was clear, understandable, and conducive to capturing critical thinking processes effectively. Additionally, piloting the protocol created space for refinement and fine-tuning of the think-aloud protocol, optimizing the study's validity and reliability.

Transcription

Each of the verbal protocols was self-recorded and conducted by participants utilizing a free screen-capturing software compatible with their machine and later transcribed by the researcher. A transcript is a, "written verbatim word-for-word account of verbal interaction" (Gale et al., 2013, p. 2). A transcription key was included to assess tone, which conveyed meaning beyond words (Bird, 2005). In order to properly analyze and understand the data later on, voice inflections, sarcasm, surprise, and hesitation, among many other tones were noted. In an effort to preserve data meaning, maintain response depth, and to offer room for interpretation and analysis, transcribing tone was an integral component of the methodology, capturing humor, sarcasm, and excitement (Lapadat & Lindsay, 1991). As this research had the potential to inspire sensitive subjects, pseudonyms were utilized in transcription, as advised by Glesne (2011). The participants' real names were utilized until all data was collected, and then their names were transferred to pseudonyms in transcription. Despite the use of pseudonyms, students were referred to collectively as "student" in the findings. This decision stemmed from the study's focus, which did not aim to differentiate between individual participants or analyze variations in their responses. Instead, the data was presented as representing a homogeneous group, emphasizing shared experiences and patterns rather than individual distinctions. Transcripts had large margins and adequate line spacing for coding and notes (Gale et al., 2013).

Methods for Data Interpretation

The objective of the data analysis was to interpret and synthesize the data in order to derive meaning and insights to contribute to our understanding of student fashion designers' critical thinking in the 3D environment. The protocol analysis adopted the coding model of the THREAD framework. The coding scheme of this study was divided into the three critical thinking categories of the framework: (1) problem solving, (2) reflexivity, and (3) individual agency. The designers' protocols, obtained from video recordings, were transcribed for both verbal utterances and relevant actions and segmented into small units of thought and each instance of verbalization/salient action was examined for its alignment with these categories. Out of all data analysis methodologies that exist in the design cognition literature, protocol analysis has received the most positive attention and use (Ericsson & Simon, 1993). Verbal protocol analysis has, "become regarded as the most likely method (perhaps the only method) to bring out into the open the somewhat mysterious cognitive abilities of designers (Cross, 2001, p. 80).

In alignment with Flower and Hayes' (1981) direction for utilizing the think-aloud protocol, verbalizations were not categorized according to levels and all levels were valid, including introspective and inferential thoughts. Student designers working in CLO were instructed to, "verbalize everything that went through their minds as they [designed], including stray notions, false starts, and incomplete or fragmentary thought" (Flower and Hayes, 1981, p. 368). Thematic analysis was employed to identify recurring patterns, themes, and sub-themes within each critical thinking category. This process involved utilizing constant comparison and systematically organizing the coded data to derive explanatory themes related to each category (Strauss & Corbin, 1990). In addition, connections between the different critical thinking categories were established, exploring how they intersected and influenced one another within the 3D design process, facilitating the categorization into groups across participants (Janabi et al., 2013). A comprehensive narrative, blending both descriptive and explanatory elements (Ritchie & Lewis, 2003), was crafted to organize and scrutinize quotations; Quotes were carefully chosen to exemplify the identified themes and highlight the notable variations in participants' narratives during the protocols. This integrated approach provided a holistic understanding of the dynamics of critical thinking at play when student designers engaged with 3D simulation software.

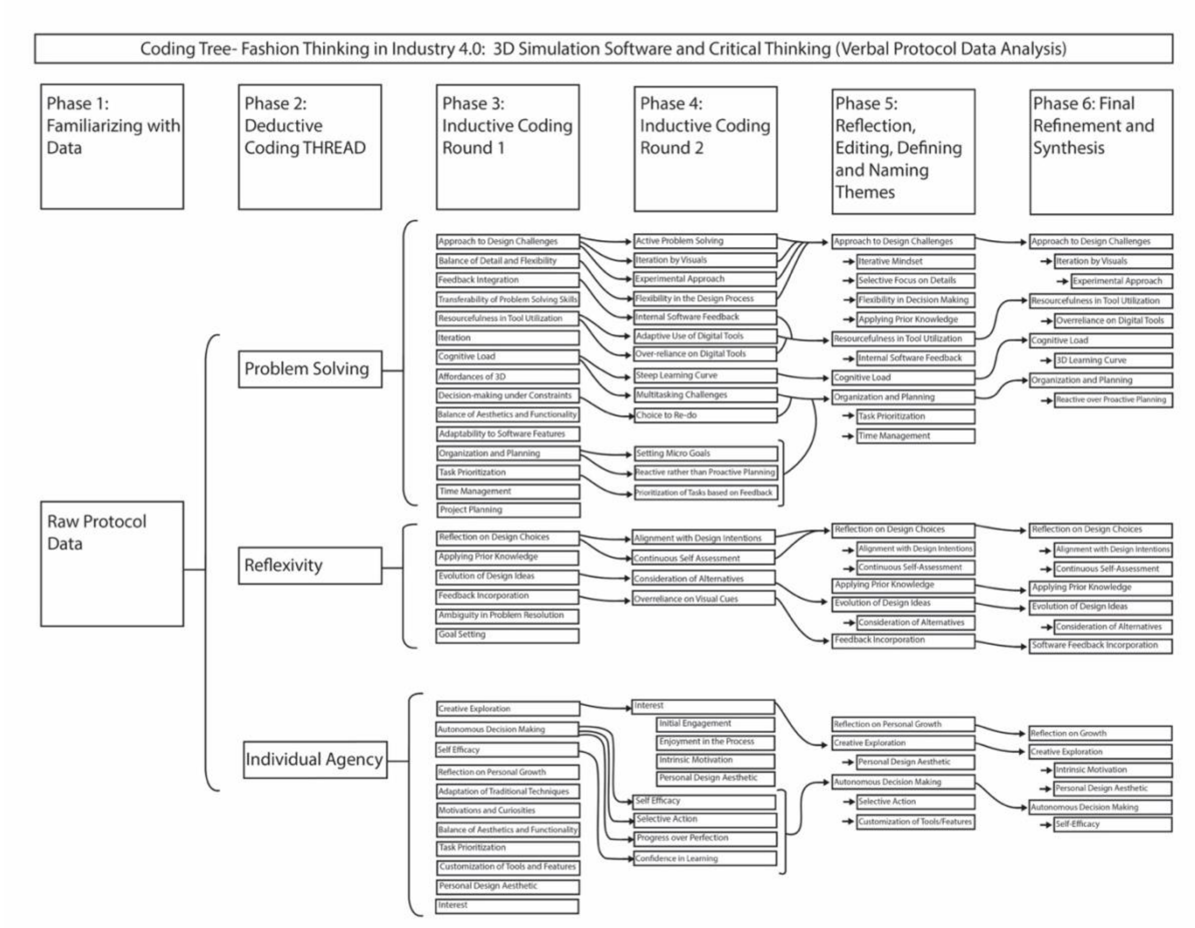
The verbal protocol data were analyzed thematically by the identification of patterns and common themes tying back to the 3 relevant tenets of the THREAD framework. According to Gale, Heath, Cameron, Rashid, and Redwood (2013), an analytical framework, which in this study was the THREAD model, is a “set of codes organized into categories that have been jointly developed by researchers involved in analysis that can be used to manage and organize the data” which was employed to summarize and reduce the data to answer research questions (p. 1471). Analysis of the verbal protocol data involved a thematic approach in an attempt to understand underlying meanings and messages conveyed by the critical thinking identified. The overarching categories were understood as clusters of codes, which are descriptive or conceptual labels assigned to excerpts of raw data (Gale et al., 2013). Saldaña describes codes as, “a word or short phrase that symbolically assigns summative, salient, essence capturing, and evocative attribute for a portion of language-based or visual data” (2021, p. 5). Codes were grouped into categories that are similar and interrelated, in an effort to begin to abstract out the raw data. The categories aligned with that of the THREAD framework's three tenets, which were the overarching themes, or interpretative concepts describing the data (Gale et al., 2013).

Saldaña's (2016) work informed the structure and process of coding the data in this study. The two-part coding cycle he outlined was instrumental in organizing and analyzing protocol data gathered from undergraduate fashion design students using 3D simulation software to create collections. His discussion in Chapter 11, which focuses on theme development, was particularly relevant for connecting codes to the THREAD framework, which outlines seven tenets of critical thinking in virtual fashion design—three of which (problem-solving, reflexivity, and individual agency) were central to this research. Additionally, Saldaña's emphasis on the interpretive nature of coding resonated with the qualitative approach employed in the study (2016). This guided the researcher in adopting a reflective and thoughtful coding process to uncover insights into critical thinking within the virtual environment. Saldaña's guidance on analytic memos was also invaluable, as these memos provided a means to document and reflect on the analytical process, facilitating a deeper interpretation of the data (2016).

Coding Process

The coding process for this study was designed following the principles outlined by Saldaña' (2016). This multi-phase approach ensured a systematic and thorough analysis of protocol data, which facilitated a deep understanding of the THREAD framework's application to fashion design and critical thinking in virtual environments. The coding process is exemplified through a graphic (Figure 3.2). Through multiple rounds of coding, the researcher progressively segmented, classified, and synthesized data, to align findings with the critical thinking dualities within the THREAD model of Problem Solving, Reflexivity, and Individual Agency.

The process began with an overview of the data. Each data set was reviewed in its entirety to understand its context and meaning, with initial notes capturing salient phrases, action descriptions, and sentences. Each new set of data was analyzed individually while ensuring consistency across all sets. Salient portions were segmented into meaningful units and assigned to specific codes derived from both deductive and inductive approaches. The first round of coding focused on descriptive and initial observations, laying the groundwork for subsequent analysis. In the second round, a deductive coding approach was applied, aligning segments of data with the THREAD framework, specifically focusing on critical thinking dualities such as Individual Agency, Reflexivity, and Problem-Solving. This structured approach ensured that the foundational elements of the framework were systematically integrated into the analysis. During the third round, an inductive approach was employed, enabling the identification of emerging themes. Phrases and action descriptions that did not initially align with the THREAD framework were grouped and explored to uncover additional patterns and themes and sub-codes were created under each initial code. The fourth round involved reflecting on and refining the codes across all data sets, ensuring that they accurately represented the data's content and meaning. This step also helped ensure consistency across the nine data sets, allowing for a more cohesive analysis. In the fifth round, all coded data were compiled into a single document where codes and sub-codes were organized under the THREAD framework, with corresponding analyses and relevant quotations included. This stage involved scrubbing the data for inconsistencies, overlaps, and any ambiguities. Finally, in the sixth round, a holistic review of all data sets was conducted. The final refinement process expanded and reorganized codes to create a comprehensive and nuanced understanding of the data in relation to the THREAD framework



(Figure 3.2).

Figure 3.2

Coding Tree: Fashion Thinking in Industry 4.0: 3D Simulation Software and Critical Thinkin

Trustworthiness

According to Chambliss and Schutt, the act of research and observation makes a certain unnatural environmental element unavoidable (2019). As students' screens were recorded, they had a heightened awareness of their actions which may have had some effect on the results. The participants were thoroughly briefed that there are essentially no wrong choices or ways to think and design and that the study objective was to glean an understanding of their processes.

In this qualitative study that utilizes a naturalistic inquiry approach to elucidate and archive fashion design cognition within 3D simulation software, several principles were employed to ensure research quality. Specific to naturalistic inquiry, credibility, transferability, dependability, and confirmability were considered (Lincoln & Guba, 1985). While I served as the instructor for the courses from which participants were recruited, this role did not significantly impact my findings beyond providing access to the student participants. My position did not influence the interpretation of results, as the study focused on documenting their critical thinking processes rather than assessing their skill levels or performance. Additionally, participants were encouraged to engage in their natural workflows without concern for evaluation, reinforcing the study's emphasis on authentic cognition.

Credibility

In qualitative studies, researchers acknowledge that each participant brings their unique perspective and understanding of reality and this recognition of multiple truths underscores the importance of capturing diverse viewpoints and experiences in the study (Erlingsson & Brusiewicz, 2013). By embracing the ontological assumption of multiple realities, this research aimed to explore the rich tapestry of subjective realities and interpretations that presented when thinking in the 3D space, ensuring that the findings reflected the complexity and nuances inherent in human experiences (Lincoln & Guba, 1985).

Transferability

Transferability, or the extent to which findings can be applied to other contexts or populations, was addressed through detailed descriptions of the research methodology, including participant selection criteria, think-aloud procedures, and data analysis techniques (Erlingsson & Brusiewicz, 2013). Additionally, the study aimed for saturation, wherein data collection continued until no new insights or themes emerged, thereby increasing the likelihood that findings were relevant and transferable to similar contexts or populations.

Dependability

Dependability refers to the stability and consistency of the research findings over time (Erlingsson & Brusiewicz, 2013). In this study, dependability was ensured through careful documentation of the research process, including detailed records of data collection and analysis procedures. Another way to show consistent findings, and therefore, dependability, was through "peer scrutiny to minimize inconsistencies and achieve clear and logical documentation" (Erlingsson & Brusiewicz, 2013, p.98). Additionally, peer debriefing and investigator triangulation was utilized, involving multiple researchers in data analysis to confirm findings and interpretations, thereby enhancing the credibility of the study.

Confirmability

Confirmability is defined as, "a degree of neutrality or the extent to which the findings of a study are shaped by the respondents and not by researcher bias, motivation, or interest (Erlingsson & Brusiewicz, 2013, p.98). To enhance confirmability, the researcher employed reflexive journaling to reflect on their own biases and assumptions and how these may have influenced the research process. According to Cowan (1998), much of the trustworthiness in naturalistic inquiry is found in the utilization of reflexive journaling. By critically reflecting on their background and experiences, the researcher aimed to mitigate the influence of personal biases on the interpretation of findings, thereby enhancing the validity and credibility of the study.

Methodological Transparency

Methodological transparency was prioritized by clearly articulating the research design, data collection methods, and analysis techniques. Specifically, verbal protocols were utilized to observe critical thinking within the 3D simulation software environment among student designers, utilizing the THREAD framework. Participants' screens were recorded as they worked through designing a collection (either capsule or senior capstone), providing rich data that captured their critical thinking. This transparent approach allowed for the documentation of participants' experiences while working with 3D simulation software, which ensured clarity in data collection and analysis procedures.

Through the application of these principles, this qualitative study aimed to ensure research quality and rigor in assessing critical thinking in the virtual environment. By adhering to methodological transparency, reflexivity, and member checking, the study sought to provide valuable insights into the critical thinking involved in fashion thinking within the virtual environment, thereby contributing to the advancement of knowledge in the field.

Findings

This study investigated the critical thinking processes of student fashion designers as they navigated 3D simulation software. Through the lens of the THREAD framework's tenets of critical thinking— problem-solving, reflexivity, and individual agency—the analysis revealed how students engage with complex design challenges, make reflective choices, and manifest their unique design vision in the virtual workspace. To uncover the intricacies of their critical thinking, verbal protocol analysis was employed to capture students' real-time thoughts and decision-making as they worked through design tasks in 3D CLO.

Each tenet of THREAD offered a distinct perspective on these interactions. The problem-solving dimension findings centered on how students approached design obstacles, planned and prioritized, utilized digital tools, and managed cognitive load while iterating through visuals and internal feedback mechanisms in 3D. In exploring reflexivity, the findings revealed the ways students reflected on their design choices, reconsidered initial concepts, applied prior knowledge, and integrated feedback to refine their ideas specific to the virtual environment. Finally, under individual agency, the study results highlighted the students' reflection on their growth, creative exploration, and self-efficacy, which together underscored their independent decision-making and creative autonomy within the software environment.

This structured examination of students' critical thinking in the environment created by 3D simulation software illuminated not only students' strategic responses to design challenges but also the reflective and agentic dimensions of their critical thinking. Together, these findings contribute to a deeper understanding of how critical thinking—an essential duality within fashion thinking—emerges within the virtual design environment.

Problem Solving

Findings displayed how problem-solving emerged as a critical thinking tenet in the 3D design environment through students' approaches to design challenges, resourcefulness in tool utilization, management of cognitive load, and approaches to organization and planning. Students demonstrated adaptability, experimentation, and a balanced focus on aesthetics and functionality as they navigated design challenges in CLO. The software enabled iterative adjustments and real-time visual feedback, which was found to foster creativity and quick solutions. However, its trial-and-error nature and lack of tangible consequences often discouraged deliberate decision-making and reflection. Additionally, at times the steep learning curve shifted focus from design to technical troubleshooting, underscoring the importance of integrating reflective practices and foundational skills alongside 3D tools in fashion design education.

Approach to Design Problems

This section examines how students used problem-solving to address design challenges in 3D fashion software, highlighting CLO's immediate feedback and low-risk environment, which fostered adaptability, experimentation, and confident engagement with design issues. The adaptable, trial and error-based approach to design problems and solution finding in 3D fashion software was exemplified by a statement made by a student addressing an issue with the bodice shape, “I don’t necessarily like the way that it kind of sticks out. Let’s see if we can do something about that.” This swift engagement with the challenge at hand, marked by a certain confidence and creative freedom, reflected a sentiment shared by many students and was likely fostered by CLO's immediate feedback and low-risk environment. Unlike traditional methods—where a single change would require purchasing new drafting fabric, manually adjusting the pattern, cutting, pinning, and stitching—students in CLO simply hit "command z" to undo mistakes and unwanted outcomes, which encouraged experimentation without consequence.

Throughout this process, students also drew upon prior knowledge and instruction to guide their decisions, effectively blending free experimentation with learned techniques. For instance, one student recalled, “I remember in class learning that the point needed to be red,” revealing an ability to apply in-studio classroom learning directly within CLO. This combination of instructional recall and flexible experimentation illustrated how CLO empowers students to make confident design decisions by balancing past learning with creative freedom. They adapted their methods on the spot, showing a readiness to explore alternative solutions when challenges arose. For example, one student, faced with a complex garment arrangement in the 3D window, reflected, “I’m guessing there’s way easier ways to do what I’m doing that would take way faster, but... I might reset this 2D arrangement.” This adaptability, even in the absence of a clear solution, underscored students' problem-solving approach, characterized by experimentation and refinement in real time. Adaptability was also evident as students confronted software-specific challenges. When one student encountered a seam overlapping error, they recognized the issue and responded with flexibility, saying, “Is it going to yell at me? Yes, it is,” right before immediately adjusting their approach by splitting segments. This response highlighted their growing comfort with CLO’s tools, as they learned to navigate its limitations and features in real time. Similarly, another student reflected on the shift from estimating measurements to using precise inputs, noting, “When I learned this [inputting specific measurements], it changed my life because before this I was just estimating.” This progression from guesswork to precision underscored adaptability and capacity to adopt more sophisticated methods in the future as students become more familiar with the software’s capabilities.

Additionally, the problem-solving process in CLO was found to be iterative, with students checking measurements and incorporating visual software feedback as they refined their designs. Statements like “Okay, so now, it's kind of like a really boring shape, so I have to adjust that,” showcased their awareness of the evolving nature of the design. Despite admitting limitations in skill, one student expressed an openness to trial and error, saying, “I'm not a pro at it yet. I have a lot to learn, but just experimenting and kind of going according to feelings can be helpful.” Echoed by many students, 3D simulation software encouraged an intuitive approach, where experimentation was key. One student noted, “I think, plopping them on randomly and then adjusting them in the 2D window is actually being more helpful for this,” underscoring students' reliance on on-the-fly adjustments. Overall, students' approaches to design challenges in 3D centered on flexibility and a willingness to adapt their strategies and aim.

This adaptability was evident in their problem-solving methods, which emphasized iteration and responsiveness to the unique demands of the digital environment. In the 3D design environment, students approached problem solving through an iterative process that relied heavily on visual cues and software feedback. CLO provided critical internal feedback that informed adjustments by way of a 3D window that updates immediately, and student were found to rely these real-time feedback features, such as stress maps, to guide refinements. As one student noted, "CLO can kind of shed light on where there's fit concerns," demonstrating that they look to visuals generated by the software to gain insight into problems, instead of addressing the patterns directly. This internal feedback drove iterative decision-making, as students continually evaluated and addressed the design's visual congruency. Students often "eyeballed it" in the virtual environment, making quick, intuitive adjustments rather than following the meticulous calculations and measurements required in traditional patternmaking. One student's process illustrated this instinctive approach: "And bring this down just a little. Bring that down just a little," they said, reflecting how small visual tweaks were used to reach the desired look. While this method allowed for refinement, it may have limited students' ability to step back and evaluate the design as a whole. This fragmented focus may result in a less cohesive and intentional final product, as students prioritized addressing individual issues over developing a comprehensive strategy.

When addressing a fit issue, another student commented, "I don't like the way it's hugging so tight around the hips." This less rigid, more intuitive style contrasted with the precision-based methods typical of physical patternmaking. The software's visual feedback mechanisms prompted students to experiment with numbers, instead of entering precise and pre-calculated measurements. When adjustments to a pattern depth didn't yield the desired result, a student noted, "Look over at that on the avatar. That's still really shallow," before modifying the measurement incrementally: "We're going to change it to eight. And we're going to see how that works," and later, "I'm going to try that again. And we're going to do it at 7.5." This experimental, visual-driven process was a recurring theme in students' workflows from all protocols analyzed.

Practical adjustments, like shortening overly long sleeves, reflected a balance of aesthetics and functionality: "I don't like how long the sleeves are... I like a bunchy sleeve, but these are excessive." The ability to blend visual and functional elements was further enhanced by CLO's visual feedback, enabling students to "go more by visuals," as one student purported. They also embraced design features that pushed creative boundaries, such as a dramatic curved hem: "I like how this is like a super curved hem, which is something I would have probably never thought to do in real life, but I kind of love, like the dramatic effect of it, you know?" Together, these insights revealed how students employed adaptability, experimentation, and a dual focus on aesthetics and practicality to navigate and solve design challenges effectively within a virtual 3D environment.

This experimental approach is particularly fostered by the unique capabilities of the software itself, which encourages exploration. The virtual environment of software like CLO removes the permanence of physical materials, enabling students to engage in trial-and-error problem-solving without the fear of irreversible mistakes. This freedom fostered an iterative mindset, where designers continuously tested, adjusted, and refined their work. As one student described, "By the end of my capstone project, I'm just going in and editing patterns in CLO every day," reflecting the daily practice of refinement. The visual feedback discussed plays a significant role in guiding these iterations, with students frequently simulating their designs to assess and refine their choices. Comments like, "Really quick, I'm just going to try to simulate that one part and see what happens," underscored the emphasis on immediate results to inform subsequent adjustments. This reliance on visual evaluation was further supported by the ease of using commands like "undo" to backtrack and try alternative approaches. The statement, "Oh, let's not do that," followed by command z, reflects this ease, which may reduce opportunities for deeper reflection and intentional decision-making. The flexibility of the virtual tools, while enabling creativity, did seem to create a problem-solving approach where students focused on fixing immediate issues rather than anticipating and preventing them. This reactive approach risks diminishing the development of proactive planning skills, which are essential for tackling complex design challenges.

Additionally, the reduced consequences for mistakes in the virtual environment often led to a less disciplined approach to design. Unlike physical methods, where errors can have costly and time-consuming implications, digital tools encourage experimentation with minimal stakes. As one student remarked, "I can just mess with it until I feel like it's good," illustrating a reliance on iterative adjustments rather than deliberate, well-considered choices. This lack of consequence can undermine the development of critical foundational skills, such as precision and preemptive problem-solving, which are vital in traditional design practices.

Resourcefulness in Tool Utilization

Despite these challenges, students demonstrated adaptability and resourcefulness in learning and applying the tools essential for 3D design. For example, one student optimized their process by using the symmetry tool, noting, "I'm going to make it a symmetric pattern. With sewing, I like to do symmetric patterns like this." This strategic choice saved time and ensured balance, as any adjustments made to one side of the pattern piece automatically applied to the other. Such efficiency reflected a mindful approach to managing virtual tools for better workflow and design consistency, an approach observed in many of the protocols.

In addition to symmetry, students creatively employed software functions to emulate hands-on techniques from real-world garment construction. For instance, one student adjusted fit by "pinning it to itself like I would if I was doing alterations," skillfully transferring skills from the physical to the virtual space. When encountering constraints, such as sewing overlaps or software errors, students employed their iterative skills to swiftly adjust in order to keep progressing. For instance, when an overlapping seam triggered an error, a student reconsidered their approach, saying, "Maybe instead of doing it that way, maybe we can just make these smaller segments." They then used the add-point tool to divide the seam line, quickly adapting their technique and employing digital tools to resolve the issue.

While resourcefulness in tool utilization was a hallmark of students' adaptability in 3D design, there is a potential risk of over-reliance on digital tools that may hinder the development of foundational skills essential in traditional design methods. The constant experimentation facilitated by software features, as one student noted, "I'm not a pro at it yet," highlighted a tendency to rely on the tool's capabilities rather than a deep understanding of design principles and pattern-making skills. This reliance sometimes led to a superficial engagement with the creative process, where students depended on the software to correct or refine their work instead of cultivating the precision and intentionality required in physical methods. Moreover, the availability of automated features in CLO, like the grading tool, pleating tool, and walking tool, detracted from students' ability to manually calculate and execute technical design features, potentially creating gaps in their skill set that may limit their versatility in non-digital environments. This over-reliance underscored the importance of balancing digital experimentation with a strong foundation in traditional practices to ensure a comprehensive design education.

Cognitive Load

Cognitive load fell under problem-solving as students managed the mental demands of translating their design ideas into digital commands while navigating software limitations and multitasking, requiring them to develop strategies to overcome these challenges effectively. While the 3D environment introduces layers of complexity and cognitive strain due to the need to translate ideas into digital commands, for some students, it also serves as an empowering tool. The physical construction process can impose a significant cognitive load, particularly for those who struggle with sewing techniques and material manipulation. In contrast, the digital environment allows them to focus on design decision-making without being hindered by technical sewing challenges. However, frustrations with software functionality still impacted design flow, requiring adaptability and resilience to maintain creative momentum. For instance, one student's experience with pleats exemplified this shift: "I always have issues with the pleats in CLO. For some reason, it always gets a little funky." The unpredictable behavior of digital pleats introduced the trial-and-error process that ultimately distracted from design intentions. Similarly, when stitching features did not perform as expected, students pivoted to alternative methods. For example, one student switched to M:N stitching when free sewing became unworkable. Statements like, "I thought I could drag it... but I guess I can't," illustrate how software constraints complicate decision-making, demanding on-the-spot adjustments. Software performance issues also offered opportunities for building resilience and adaptive thinking. One student observed, “Sometimes this thing just moves so slow,” and these moments of delay required students to recalibrate their workflow and adjust their pacing. Working in a virtual rather than physical space demands an even higher level of mental flexibility, as students must adapt their creative process to digital tools that lack the tactile experience of garment construction. Adapting to tasks such as positioning pattern pieces in an intangible 3D space with arrangement points, one student noted, “It’s never in the spot you want it to be”, requires students to refine their visual estimation skills.

The steep learning curve of 3D design software like CLO introduced a significant cognitive load for students, akin to learning a new language. As students adapted to the virtual environment, they often grappled with unfamiliar tools, a workflow that differs from physical patternmaking, and an array of functions that required time and effort to master. Comments such as “I’m guessing there’s way easier ways to do what I’m doing” reflected the inefficiencies inherent in the early stages of learning, where students spent considerable energy troubleshooting technical issues rather than focusing on the creative aspects of design. This redirection of mental resources may dilute their engagement with broader design goals, limiting their ability to think critically and holistically about their work. Students navigated a digital environment that often felt counterintuitive or overwhelming, as they translated their design ideas into the logic of the software. This translation process was found to be mentally taxing, especially as students’ foundational coursework is based in physical design methods. This steep learning curve not only increased cognitive load but may have also resulted in frustration and reduced confidence, as students struggled to balance creative exploration with technical competency.

Organization and Planning

Organization and planning emerged as a key theme under problem-solving as students actively prioritized tasks, sequenced their actions, and managed their time in response to immediate software feedback. The 3D environment encouraged them to strategize their process, often focusing on high-impact elements rather than minor details initially. For instance, one student decided not to focus on the neckline early on, saying, "I'm not going to be super particular about this," and instead prioritized the hood construction, a larger design component that required more time: "But for the sake of time, I'm just gonna get started on the hood. I think it'll take a while." This approach highlights how students adjusted their workflow to allocate their effort.

Frequent progress checks within the software fostered a strong awareness of time management. Statements like "It only took a half an hour", and similar statements of time passed, revealed how students monitored time spent on tasks, allowing them to stay on track. This time awareness was present in a majority of the protocols, and it appeared to guide their workflow, as they intentionally tackled foundational steps first—such as sewing all pieces together, drafting out complex patterns, such as hoods, and assessing the overall fit—before refining smaller details, like adding pockets, zippers, or topstitching. Students often focused on specific aspects of the design process to maintain momentum and manage the complexity of tasks. This micro-goal setting was evident in comments like, "I still need to figure out exactly how the details of this sewing need to go." By breaking the larger design process into smaller, manageable tasks, students focused their energy.

Despite evidence of micro goals, students' planning often appeared more reactive than proactive. In the physical environment, tangible interactions with materials and tools naturally structure the design process, guiding logical sequencing. Handling fabric reveals properties like drape and stretch, prompting early design adjustments, while tools like sewing machines inherently dictate a progression—sewing seams before topstitching, for instance. Immediate visual and tactile feedback helps designers identify and resolve issues, and prototyping methods, such as pinning fabric on a dress form, intuitively highlight next steps. Comments like, "Okay, so I realized that I didn't add in the slit for the skirt. So I'm going to go do that," or, "I shouldn't have done that first," reflected a tendency to address oversights as they arose, resulting in inefficiency and backtracking. These reactive patterns highlighted the importance of proactive production and patternmaking planning in digital design, where tools like CLO and other 3D simulation software rely on abstract representations and lack the immediate sensory feedback of physical materials. This need for proactive planning connects directly to the broader analysis of problem-solving as a critical thinking skill in virtual fashion design, emphasizing how it manifests uniquely in the 3D environment.

This analysis of problem-solving revealed that while 3D simulation software fosters adaptability, experimentation, and a balance between aesthetics and functionality, its ease of trial-and-error sometimes hindered reflective decision-making. The software's speed and creative freedom, combined with its technical complexity, often shifted focus from design intent to troubleshooting. These dynamics underscore the importance of teaching strategies that promote intentional, reflective practices alongside the innovative possibilities of 3D simulation tools.

Reflexivity

Reflexivity played a key role in critical thinking within the 3D design environment, as students actively reflected on their design choices, applied prior knowledge, considered alternatives, and incorporated visual feedback to refine their work. The real-time insights provided by the simulations enabled iterative adjustments and fostered active engagement with the software. However, this continuous feedback loop was found to sometimes lead to superficial reflection, with students focusing on immediate visual adjustments rather than deeper critical analysis of their design decisions.

Reflection on Design Choices

This tendency toward superficial reflection highlighted the need to explore how students engaged with deeper, more intentional reflection on their design choices, a critical aspect of reflexivity in the 3D design process. In the 3D design process, students engaged in continuous reflection and critique, leveraging the software's visual responsiveness to assess and refine their work. This iterative approach allowed them to evaluate key design elements like fit, proportion, and alignment, which are crucial in creating aesthetically and functionally successful garments. As one student put it, "I'm not entirely happy with that," highlighting a persistent process of reassessment. This kind of self-evaluation was central to their design thinking and encouraged constant refinement as they worked towards their ideal outcome. Another student reflected, "Why is it doing that, though?" signaling a deeper questioning of the design's behavior and potential areas for improvement.

Students also demonstrated the ability to align their evolving designs with their original intentions, often using reference materials such as sketches and mood boards. For example, one student said, while toggling their screen to a page of fashion illustrations, "I know in this sketch I drew a lot of segments, but I think I want to shorten that to just eight pieces," showing a thoughtful adjustment of their design based on original concepts. This reflection allowed students to refine their ideas in the virtual space, ensuring their designs maintain coherence with the overall vision.

Self-assessment played a significant role throughout the 3D design process, with students regularly evaluating their progress and making adjustments. For instance, a student commented, "That worked out pretty well...maybe it’s a little bit too small," demonstrating a critical evaluation of both successes and areas that still require attention. This constant feedback loop was evident as they refined the garment fit, such as when another student stated, “I don’t like how long the sleeves are... I’m going to shorten them.” This statement illustrated their willingness to revise design choices based on real-time feedback. Additionally, moments of pause for reflection were common, as seen in the phrase, “I think I’m just going to undo all that and think.” In this scenario, the student was having difficulty getting the virtual seams to align. Their pause represented a deeper level of reflexivity, where they took time to reconsider their design strategy before proceeding. These moments of clarity—such as one student noting, “I’m having a moment of clarity and reflection, thinking that this does not make very much sense because I’ve seen about 20 million patterns, and this one doesn’t make any sense”—highlighted the value of stopping to reassess not just the details of a design but the broader logic behind their choices.

Applying Prior Knowledge

These reflective moments often prompted students to connect their insights with prior knowledge, bridging their understanding of traditional garment construction learned in the classroom with the challenges of navigating the 3D design environment. In CLO, students frequently drew on prior knowledge from their experience in the classroom, where they learned traditional garment construction. This transfer of skills exemplifies reflexivity, as students critically evaluated and adapted their existing knowledge to navigate and problem-solve within the digital platform. By reflecting on their prior experiences, they bridged the gap between physical and virtual design, applying critical thinking strategies in innovative ways. For instance, one student reflected on their past experience, saying, “I did a couple hoods for capstone... it took a while, re-tweaking them,” and then went on to explain their familiarity with the general shape and silhouette of a 2-piece hood, informing their direction in CLO. Students’ traditional garment-making skills, such as fitting and pattern manipulation, remained crucial in the virtual design process. In particular, familiar techniques were employed when students needed to refine the fit or structure of digital garments. One student said, “And I'm just pinning it to itself like I would if I was doing alterations,” when addressing a fit issue with their skirt. This showed a reliance on traditional techniques, such as pinning, to make adjustments to the digital garment. This approach not only demonstrated their comfort and reliance on physical garment-making methods but also underscored their understanding of the translation of these tools and strategies from one environment to the other. The ability to adapt traditional design methods to the 3D environment was observed across nearly all protocols where students' displayed capacity to leverage past experiences to solve new challenges.

Consideration of Alternatives

As new challenges emerged, students’ design ideas evolved, reflecting a fluid and adaptive creative process that incorporated reflection and experimentation. As they refined components like the skirt and bodice, they made adjustments that showed an openness to change based on emerging insights. For example, one student decided to alter the skirt shape for a '50s-inspired silhouette from an A-line, noting, “So now it's kind of like a ‘50s style with like the bel, kind of a bell shape.” This shift indicated an evolution from their initial concept as they responded to new unexpected ideas that enhanced their design's aesthetic impact. This adaptive approach was also evident in smaller details, like when another student revisited the decision to add darts, “Actually we can come back in here and add that dart again.” Such choices highlighted the fluidity of their design thinking, where reflection drove the ongoing refinement of elements. This reflective process not only shaped their decisions but also fostered a mindset geared toward innovative adaptation.

Students displayed this adaptability by considering alternative solutions when challenges arose, demonstrating a flexible and strategic approach to design in 3D. They explored alternate ways to streamline the construction process, as reflected in a student's thought, “Oh, I could cut it this way... less seamlines, less sewing.” Here, this student described merging the cups of her corset with the rest of the bodice, simplifying the work by reducing seamlines. This willingness to consider alternative ideas was echoed when another student decided to change angular seams to curve points, emphasizing that this change may improve the overall design aesthetic. Through continuous reassessment of design alternatives, students engaged with the 3D environment in a manner that combined creative exploration with varying levels of reflection. While some reflections were fleeting, students demonstrated an ongoing process of reconsidering their choices and adjusting designs.

Software Feedback Incorporation

Incorporating feedback from the software itself played a central role in reflexivity, a key tenet of critical thinking. Reflexivity involved a continuous cycle of self-assessment, where students engaged with feedback to assess and revise their design decisions. In the digital space, real-time visual feedback from the software prompted students to reassess and adjust their designs iteratively. As one student mentioned, “I kind of like to experiment... sometimes that bites me in the butt, but sometimes it kind of works,” reflecting how trial and error, a critical component of reflexive practice, contributes to growth and learning in the digital design environment.

One drawback of the ongoing feedback loop that enhanced reflexivity afforded by the 3D space was superficial reflection. Students made visual adjustments—such as shortening a sleeve because it "looks off"—without fully considering how the change would affect other critical elements of the design, such as fit, movement, or the garment's functionality in physical production. This focus on immediate, visual feedback detracted from more in-depth reflection on the broader implications of their design choices. For example, another student noted, “Now the underarm on the back looks like it’s kind of cutting into her a little bit,” using this visual insight to improve the fit. Instead of addressing deeper design principles and applying an understanding of waterfall adjustments in patternmaking, students inadvertently prioritized surface-level changes that did not always contribute to the garment's functional success. This reflected a potential limitation in reflexivity, where the process of continuous adjustment was not always paired with a deeper, more strategic reflective approach.

Individual Agency

The analysis of students' verbal protocols revealed how individual agency manifests as a tenet of critical thinking in 3D fashion design. Key findings highlighted students’ reflection on personal growth, creative exploration, and autonomous decision-making.

Reflection on Growth

This active reflection on their skills and development was a key component of agency, as it illustrated students taking ownership of their learning journey, recognizing their progress, and making intentional choices to navigate and grow within the virtual design space. For instance, one student reflected, “When I first started doing hoods in CLO, they looked goofy at first,” while drafting a hood in CLO during the protocol. This highlighted their awareness of personal progress and evolving proficiency in using the design software. Similarly, a comment like, “I’ve lost a little bit of skill, just since I haven’t used the program since, like, December,” revealed an understanding of the impact of practice on skill retention and the learning curve they experience in regaining proficiency. Further reflection on growth was seen as students discovered new tools and techniques. For example, one student exclaimed: “So can I go smart arrangement on those other ones too? Actually, I feel like I just discovered something,” after realizing the utility of a newfound tool, and later acknowledged, “Let’s see. So one thing I learned... is the power of internal lines,” when drafting front facings for a bodice. These moments highlighted the students' recognition of novel skills and their ability to adapt and build on previous knowledge within the software.

Creative Exploration

Building on this adaptability and recognition of new skills, students also demonstrated individual agency through creative exploration, leveraging the virtual environment's flexibility to experiment and push boundaries beyond traditional industry constraints. One student observed, “Obviously, if I was sending these patterns to a factory, you can’t really risk experimenting too much,” highlighting how educational context allows for risk-taking and innovation. This freedom fostered a willingness to test new ideas, as seen in choices like adding a curved hem “for the dramatic effect,” where they exercised agency through creative decision-making. Students balanced aesthetics with functionality, as shown by the thoughtful placement of design features when a student was building out a storm cuff: “I think I’d want it to sit a little bit higher up, and there’s going to be a thumbhole.” Here, the student creatively explored the balance between visual appeal with practical considerations. Their enthusiasm for the software further fueled this creative exploration, with comments like, “It’s so fun to find new ways to do things,” and “I really love messing around with this, though. It’s super fun.” This enjoyment of the process drove a willingness to try unconventional techniques and explore the software's potential, resulting in innovative and imaginative design solutions.

This creative exploration was further supported by intrinsic motivation, which stems from a genuine engagement with the design process. Students demonstrated intrinsic motivation in their approach to their design work, as their engagement was often driven by a deep connection to personal and cultural inspirations. For instance, one student stated, “This is kind of everything that inspired me and that I wanted to incorporate into this collection,” showing a strong commitment to their creative vision as they toggled their screen to their mood board. They mentioned, “"These are Cambodian traditional fabrics… I thought was really nice to incorporate." This intrinsic drive was also reflected in nearly all participants’ processes, where students expressed a sense of enjoyment and curiosity in exploring design possibilities. As one student noted, “I just like to play around and see what the possibilities are,” illustrating a genuine interest in experimentation and discovery.

Despite the unique challenges posed by the 3D design environment, students persisted in their creative exploration, driven by the intrinsic rewards of problem-solving and achieving a design solution. The excitement of overcoming obstacles was palpable in moments like, “Oh my gosh! Did it work? (Gasps) I think it finally worked!” Their light-hearted comments, such as “Come on, little guy,” also suggested that they found enjoyment in navigating the quirks of the software. This playful attitude highlighted the students' intrinsic motivation, as they remained engaged and motivated by the process itself. Their perseverance and continued engagement, even when faced with technical difficulties, further emphasized their intrinsic motivation, as seen in statements like, “I wonder what is causing it. Okay. Instead, I’m just going to go clear around here and put one (point) here,” demonstrating resilience in their creative problem-solving. This resilience was closely tied to students’ personal vision, which served to propel them forward in the midst of challenges.

Students showcased how their personal vision guided their creative choices, resulting in designs that reflected individual identity and taste. One student began with a plus-size curvy model, sharing, “I actually started with a plus-size curvy model because it’s more closer to my body shape,” illustrating how personal identity informed her design choices. This deliberate focus on inclusivity signaled a commitment to crafting designs that aligned with a personal aesthetic and represented a broader spectrum of body types.

Throughout the process, students made stylistic decisions that conveyed their unique preferences, such as opting for “more ruching rather than pleating” or softer, curved lines to avoid “anything too harsh. Similarly, the preference for a “bunchy sleeve” and aversion to tight waistbands, “I really don’t love when a waistband is too tight...I think we’re gonna have to loosen it up a bit”, emphasized a personal style driven approach to design. Structural choices, like placing seams across the chest or adjusting the waistline to create a “cute dress,” underscored the emphasis on a personal design aesthetic. “I would probably add a seam down the center or like across the chest because I just kind of like those type of seams,” one student shared, showing how functional elements were also selected to align with their aesthetic vision. The intention to design something “classical and demure,” with careful decisions like omitting straps for a refined look, reflected students’ individuality and a coherent aesthetic direction.

Autonomous Decision Making

This aesthetically driven approach underscored the students' capacity for autonomous decision-making, as they confidently navigated the 3D design process with independence and minimal reliance on external guidance. This autonomy was especially evident in their ability to troubleshoot and experiment on their own. For example, one student addressed a fit issue by deciding, “So what I’m going to do is I’m going to move this point in quite a bit, and I’m going to move this point in more,” displaying both independent problem-solving and control over the design process. Similarly, students appeared to often prioritize progress over perfection and exhibit confidence through spontaneous decision-making. With statements like, “F*** it. I’m just going to sew it up and see how it looks,” they adopted a trial-and-error mindset that prioritized progress over perfection. One student said, “I’m just gonna command z that... Let’s do it one more time starting from the top!” The decision to move forward despite unresolved challenges, as demonstrated by statements like, “I think I’ll stick with this for now,” may lead to incomplete solutions or suboptimal outcomes compared to more thorough physical adjustments. While 3D simulation software prioritizes autonomous experimentation, speed, and adaptability, and creates space for iterative design adjustments without the constraints of physical materials, this flexibility sometimes resulted in less careful decision-making.

This sense of autonomy extended to selective choice of action, where students strategically prioritized tasks to manage their workflow. One student noted, “I’m not gonna worry about the back for right now... because I want to focus on the fun part,” showcasing their ability to focus energy on aspects of the design that excite them, while not neglecting other elements. Such decisions illustrated critical thinking and purposeful action, which helped students to navigate the complexities of digital design by balancing different priorities. This ability to make informed decisions also reflected their growing confidence in their skills and understanding of the software.

In CLO, students demonstrated self-efficacy by making independent choices about their design direction without seeking external input. They confidently navigated the design process, often saying things like, “I think I’m going to try this again.” Customizing elements such as colors and textures further highlights their autonomy, as seen in statements like, “Let’s look at what it looks like shiny” and “I want this in black.” These decisions reflected students' agency in tailoring outcomes to their preferences and creative vision. Students frequently made independent choices throughout the design process, such as “I think I’ll stick with this for now” or “Let me try something” as they experimented with new solutions. This autonomy was particularly evident when students managed difficulties on their own, as shown by statements like, “I’m going to widen this (back piece) just a touch again” and “Let’s just reset this.” These independent decisions revealed their confidence in experimenting with solutions and refining their designs without needing to rely on others.

Despite occasional difficulties, students maintained confidence in their learning process, celebrating discoveries and adjusting their approach as needed. One student reflected, “I actually didn’t know that!” indicating their openness to learning upon discovering a new tool. Their comfort with experimentation is also clear, as seen in comments like, “I kind of like to experiment and just see what happens,” suggesting they embraced the iterative process of trial and error. Even when frustration arose, they maintained confidence, saying, “Let’s try these guys and see what happens again,” showing their resilience in problem-solving. Students took iterative steps to test and adjust their designs, such as adjusting pattern pieces or discovering new tools, like the “smart arrangement tool.” One student excitedly noted, “Okay, you know what? I'm just going to use this now because I'm realizing that this is harder than I remembered." Their confidence in achieving their vision was evident, as reflected in statements like, "Okay, I think this will look a lot better," and "This is perfect." These expressions underscored their belief in their abilities and their growing self-efficacy as they refined their designs and learned.

Discussion

This study applied the THREAD model to examine how 3D simulation software, particularly CLO, fostered critical thinking within the fashion design process. By focusing on three of its seven tenets—problem-solving, reflexivity, and individual agency—the findings provided valuable insights into the model's viability as a framework for understanding and analyzing cognitive processes in virtual fashion design education. The THREAD framework successfully captured the nuanced interplay between technology and critical thinking processes, aligning well with the demands of Industry 4.0. Its metaphorical structure, inspired by the interconnectedness of threads in fabric, effectively captured and organized the critical thinking strategies employed by designers in the virtual environment. Just as individual threads are woven together to form a fabric that culminates in a complete garment, the three critical thinking tenets of the THREAD framework interweave to create the fabric of critical thinking in 3D fashion thinking. Simultaneously, the four design cognition tenets weave together and connect with the critical thinking tenets, collectively forming the cohesive garment of comprehensive 3D fashion thinking. It is important to note, however, that while design cognition and its four tenets are intricately woven into this discussion, they were not the central focus of this study. Instead, the emphasis remained on the critical thinking tenets, which, alongside the design cognition elements, form a cohesive framework for comprehensive 3D fashion thinking.

The study revealed that THREAD provides a structured yet flexible framework that organizes fashion thinking processes through the lens of critical thinking. Its focus on critical thinking through these three tenets resonates with broader educational goals, as critical thinking is increasingly recognized as essential for success in the 21st century (Da Silva et al., 2019). By utilizing THREAD, the study demonstrated how 3D tools like CLO enabled iterative problem-solving and enhanced students' reflexivity and agency in design thinking. As Cai et al. (2013) noted, the precision and manipulability of virtual objects in CLO fosters a robust platform for innovation. However, the findings also highlighted areas for improvement, particularly in addressing gaps in digital literacy among fashion students (Ernawati et al., 2022). Integrating THREAD into pedagogical curricula offers a pathway to bridge these gaps, preparing students for the complexities of contemporary fashion design (Sharkova, 2014; Ryan, 2020).

The THREAD model positions critical thinking as a cornerstone of 3D fashion thinking, equipping students with the skills to thrive in the evolving fashion industry. As virtual tools become standard, designers must master not only technical skills but also the ability to contextualize their work, integrate feedback, and innovate sustainably (Conlon & Gallery, 2023). Employers consistently prioritize critical thinking, making its integration into design education through THREAD a critical step toward aligning academic and industry standards (Society for Human Resources Management, 2008). As such, this study affirmed the THREAD model's utility as a conceptual and analytical framework for understanding the critical thinking dimensions of 3D virtual fashion design. Its emphasis on critical thinking aligns with the needs of both education and industry, offering a foundation for advancing design pedagogy in an increasingly digital world. Future work should build on these findings, exploring the broader applicability and adaptability of THREAD to other disciplines and contexts.

Problem-Solving

The iterative and interactive capabilities of 3D simulation software appeared to enhance students' problem-solving skills, which are crucial for succeeding in the fast-paced, innovation-driven landscape of Industry 4.0 (Schuh et al., 2018). Tools like CLO provide real-time feedback and enable dynamic adjustments, which allowed students to tackle complex design challenges efficiently while fostering creativity and resilience (Erboz, 2017; Debono, 2004). However, the immediacy of these tools sometimes encouraged reactive thinking, underscoring the importance of balancing adaptability with strategic planning.

While 3D environments support iterative learning cycles and align with findings that enhance educational and industrial efficiency (Fixson & Marion, 2012), they also introduce cognitive challenges. The steep learning curve was found to shift focus from creative exploration to troubleshooting, straining critical thinking and straying from design goals. Cognitive load may explain why 2D tools sometimes produce better learning gains, as shown in studies like Richards and Taylor (2015), where cognitive overload in 3D environments impacted outcomes. Conversely, other studies found 3D tools to outperform or match 2D tools, showing greater performance and appreciation of the learning environment in dental education (de Boer, Wesselink, & Vervoorn, 2015) or no significant differences in instructional design education (Ak & Kutlu, 2015). These mixed findings highlight the complexity of optimizing virtual environments for diverse educational needs.

Reflexivity

Reflexivity played a vital role in critical thinking within the virtual design environment. Immediate visual feedback from 3D software allowed students to make quick adjustments and fostered reflection. However, this reflection often emphasized surface-level visual changes rather than deeper connections to foundational design principles like patternmaking and garment construction. To enhance reflexivity as a critical thinking tool, educators should guide students toward holistic reflection on patternmaking and design principles. The THREAD framework highlights reflexivity as essential for navigating the digital intelligence demands of Industry 4.0, where designers must merge creativity with complex systems and feedback integration (British Columbia Digital Literacy Framework, 2019). As the fashion industry increasingly adopts digital tools and analytics, these skills are critical for preparing students to meet workforce demands (Rübmann et al., 2015).

Findings revealed that while students excel at iterative visual adjustments, they often lacked intentional connections to foundational principles, underscoring the need for deeper reflexive practices. This aligns with Becker et al. (2005), who recognized 3D simulation as a medium for new knowledge creation, and Papachristou and Bilalis (2015), who emphasized that 3D is a tool with the potential to integrate visualization with functional performance. With proper pedagogy, visualization and functionality can be merged in an approach to 3D fashion design learning. So, reflexivity must go beyond surface-level design to connect virtual adjustments with physical design foundations. As Cai et al. (2013) asserted, "Without pedagogy, an interactive [3D] environment will never be a learning environment" (p. 11). Educators must therefore ensure that reflexive practices in 3D design cultivate both technical proficiency and critical thinking to prepare students for the multifaceted demands of the global fashion industry.

Individual Agency

This study highlighted the significant role of individual agency in shaping students' experiences with 3D design software. Students who demonstrated self-assurance, openness to experimentation, and confidence in their abilities expressed more positive sentiments about the software and greater satisfaction in realizing their design vision. Their willingness to independently make creative decisions and engage deeply with the process—often informed by personal and cultural inspirations—enabled them to embrace the software's capabilities while maintaining focus on their creative goals. This finding aligned with research suggesting that students with positive attitudes toward 3D software are more likely to develop critical thinking skills and perceive improvements in their design abilities (Yu, 2018). Conversely, insufficient understanding of 3D tools can limit agency and hinder the design process (Ernawati et al., 2022; Avila & Pandya, 2013).

Implications for Fashion Design Education

Findings from this study underscored the transformative potential of 3D simulation software in fostering critical thinking within fashion design education. To maximize its impact, its integration must be intentional, striking a balance between virtual innovation and traditional design practices. By connecting 3D tools with foundational skills like patternmaking and garment construction, educators can empower students with the individual agency needed for success. The findings highlighted how critical thinking tenets showed up in the virtual environment as essential components of fashion thinking. While 3D software equips students to meet the demands of Industry 4.0 and supports sustainability and inclusivity, reliance on digital immediacy risks reactive decision-making. This underscores the importance of complementing rapid workflows with strategic planning (Casciani et al., 2022).

This research aligns with Green's (2015) emphasis on lifelong learning and adaptability, positioning 3D simulation as a tool that fosters creativity, resilience, and autonomy. By addressing key stages in the supply chain—conceptual design, technical design, product development, and prototyping—3D tools enable iterative experimentation and real-time feedback. To fully leverage this potential, educators must adopt a hybrid approach that preserves traditional craftsmanship while embracing digital literacy, ensuring future designers are equipped to thrive in Industry 4.0 by exercising critical thinking, reflexivity, and agency.

Expanding THREAD: Addressing Shortcomings

While the THREAD framework provided a valuable structure for analyzing and understanding design cognition and critical thinking in virtual fashion design environments, the findings from this research revealed both its strengths and limitations. While THREAD effectively outlined seven key tenets—tacit knowledge, spatial visualization, haptic memory, creativity, problem-solving, reflexivity, and individual agency—it did not fully encompass several critical dimensions of fashion thinking that emerged during the study.

One notable limitation was THREAD's inability to account for the levels of reflexivity in 3D design. THREAD treats reflexivity as a singular concept, yet the findings differentiated between reactive reflection and strategic reflection. Reactive reflection involved immediate, surface-level adjustments based on real-time feedback, while strategic reflection connected these adjustments to broader design principles and long-term goals. By failing to distinguish between these levels of reflective engagement, THREAD overlooked a distinction of deeper critical thinking that is essential in virtual environments.

Additionally, the findings underscored the challenges posed by the absence of physical touch in virtual environments, which required a cognitive shift. Without the ability to drape fabric on a dress form, manually true patterns, or feel material resistance, designers have to engage and translate differential cognitive strategies in the 3D environment. Despite these limitations, THREAD remains a useful core framework for understanding critical thinking in virtual fashion thinking. However, the findings suggest that it requires supplementation to fully capture the complexities of fashion thinking in digital contexts.

Limitations

While THREAD proved effective in this study, its application was confined to three of its seven tenets—problem-solving, reflexivity, and individual agency. The study also identified challenges that may have limited the depth of engagement with the critical thinking processes THREAD seeks to capture. Variations in students' familiarity with CLO software, combined with the constraints of a short course timeline, perhaps hindered comprehensive exploration of critical thinking in a virtual environment. The convenience sample of upper-class fashion design studio students offered valuable, context-specific insights but limited generalizability due to variations in experience and expertise based on the program. However, the focus on individual and context-specific insights aligned with the strengths of qualitative research, emphasizing depth over breadth. Additional limitations arose from the study's design, which included a brief 4-week prototyping phase and relied on 60-minute recordings of students' virtual capsule collection processes. This may have reduced the ability to capture students' critical thinking in moments of flow or during tacit, subconscious design processes. The protocol analysis methods provided a snapshot of participants' critical thinking at specific points in time but may have been insufficient to fully articulate the complexities of critical thinking processes. Furthermore, demographic data were not collected, as they were not pertinent to the study's focus on critical thinking processes within a virtual design environment. However, future research could examine how demographic factors influence engagement with THREAD, potentially offering deeper insights into variations in critical thinking approaches across different student populations.

Conclusion

This study investigated the critical thinking processes of fashion design students as they navigated 3D simulation software, specifically CLO, through the lens of the THREAD framework's tenets: problem-solving, reflexivity, and individual agency. The findings provided insight into how students engaged with complex design challenges, made reflective decisions, and manifested their unique design visions in the virtual workspace. Students displayed a remarkable ability to adapt and experiment in the digital environment, leveraging real-time feedback from the software to refine and adjust their designs. This iterative process fostered problem-solving skills, allowing students to confront design obstacles and make swift decisions without the constraints of physical materials. The freedom to experiment and modify designs quickly encouraged creativity, while the virtual environment cultivated resilience, enabling students to learn from mistakes and try new approaches with confidence.

However, this flexibility also introduced challenges. The ease of making immediate adjustments sometimes lead to a reactive design process, where students prioritized resolving short-term issues over engaging in proactive, strategic planning. The rapid pace of iteration limited opportunities for deeper reflection on design choices, potentially hindering more intentional decision-making. Additionally, while students effectively used the software's tools to navigate technical aspects, there is concern that their reliance on digital tools may result in a gap in fundamental skills, such as manual patternmaking and precision, which remain crucial in traditional garment creation. Despite these challenges, students demonstrated strong individual agency within the 3D design process. They exhibited autonomy in making creative decisions, often drawing from personal experiences, cultural inspirations, and aesthetic preferences to guide their designs. This autonomy fostered a sense of self-efficacy, as students confidently made adjustments, experimented with design elements, and engaged with the software without relying on external input. Their ability to reflect on personal growth, explore new creative possibilities, and make independent decisions highlights the importance of cultivating agency in design education.

The role of reflexivity also emerged as a key component of students' critical thinking. While the immediate feedback from the software facilitated real-time revisions, it sometimes led to more superficial reflections that focused on visual adjustments rather than deeper design considerations. To enhance critical thinking in the virtual design environment, it is crucial to encourage students to engage in holistic reflection that connects immediate visual changes with broader design principles, aesthetics, and functionality, always encouraging them to open up their pattern-making textbook. By fostering a deeper, more strategic approach to reflection, students can develop more well-rounded, intentional designs that integrate both creative and technical expertise.

Ultimately, this study underscores the value of 3D simulation software as a tool for fostering creativity, experimentation, and critical thinking in fashion design education. However, its integration into the curriculum must be balanced with traditional design methods to ensure students develop both technical skills and critical design thinking. When used thoughtfully, CLO can provide a rich environment for students to explore and refine their designs, allowing them to develop the autonomy, problem-solving abilities, and reflective skills necessary for success in both the virtual and physical design spaces. This study contributes to a deeper understanding of how critical thinking, as a duality with design cognition under the umbrella of fashion thinking, emerges and evolves within the virtual design environment, offering valuable insights for educators and future designers.

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CHAPTER 4

PAPER 3: DECODING THE ABSTRACT: 3D SIMULATION SOFTWARE AND FASHION DESIGN COGNITION

Overview

This study explored a 3D simulation design tool on learning and cognition in the undergraduate fashion design pedagogical context. Inquiring about cognition when engaged in 3D simulation software as a design tool provided valuable insight into the software's potential to improve learning outcomes, enhance design thinking and cognition skills, foster innovation, and align education with fashion industry practices. Situated in the constructivist paradigm, this qualitative study employed semi-structured interviews centered on artifacts. Utilizing a naturalistic inquiry approach, one on one artifact interviews were held to elucidate the cognitive learning processes of participants and data analysis was conceptually grounded by THREAD, a theoretical framework constructed for understanding fashion thinking in the virtual environment. Findings revealed that 3D simulation software engages tacit knowledge by allowing experienced designers to intuitively apply construction skills while beginners rely on trial and error, gradually developing design intuition. The software was found to strengthen spatial visualization by linking 2D patterns with 3D forms, enabling precise adjustments and improving proportion control. Despite the absence of physical touch, haptic memory was engaged through sensory imagination and adapted gestures, fostering immersion. Creativity flourished in 3D through rapid prototyping and real-time adjustments, though balancing structured learning with open-ended exploration was essential to prevent impulsive design choices.

Introduction

As 3D simulation software has evolved to become an increasingly integrated pedagogical tool for fashion design (Sayem et al., 2010), it has become imperative that design cognition and the learning processes specific to the virtual space is articulated. Compounding this lack of 3D design cognition knowledge is the incorrect assumption that generalized fashion design is a merely a trade centered and economic phenomenon (Schor, 2002). Most research in the fashion design field focuses on the final constructed garment or sociological and cultural context of the embodied look (Downtown, 2003). The current literary landscape presents abundant opportunity to explore the praxis of fashion design as a cognitive process and to formally capture the knowledge of the field as cognitively and behaviorally demonstrated, from a pedagogical lens.

Fashion design as praxis refers to the process in which the designer conceptualizes and actualizes a collection digitally or on-paper, including sketching initial croquis and detailing a process book, draping muslin on a virtual avatar to explore silhouette, fabric hand and garment functionality, manipulating a flat-pattern draft to achieve a certain outcome, and stitching the prototypes with an iterative method (Gully, 2010). This described nature of fashion design praxis hinges on tacit knowledge, like many art and design disciplines, resulting in a lack of understanding (Raami et al., 2010). The elucidation of process would result in an opportunity to improve fashion design pedagogy, and therefore, professional practice.

The necessity of exploring the effect of 3D simulation software as a cognitive and learning tool for undergraduate fashion design students is underscored by both industry need and pedagogical value. Due to the novelty of 3D simulation software, the cognitive process that is innate to virtual fashion design has not yet been explored. Researchers and practitioners in the fashion discipline purport that there is a significant lack of understanding of praxis (Bugg, 2009;

Finn, 2010; Griffiths, 2000) and that without the tradition of academic publishing in the field, there lacks a common understanding of fashion design praxis terminology, critical discourse, and base for common knowledge (Morley, 2013).

It is imperative to elucidate and archive the design cognition process inherent in using 3D simulation software in fashion design for several reasons. There exists a prevalent misconception that fashion design is solely a commercial enterprise driven by economic factors, overlooking its intricate cognitive aspects (Schor, 2002). By delving into the design cognition process, we can dispel this misconception and highlight the intellectual rigor and creative problem-solving involved in fashion design. Secondly, the predominant focus of existing research in fashion design tends to revolve around the final garment or the socio-cultural context of fashion, neglecting the cognitive processes that underpin design decision-making. Also, it has been recently reported by Hoang (2023) in a Business of Fashion Article that students entering the job market are lacking knowledge of emerging technologies, let alone the corresponding cognitive processes and critical thinking abilities innate to successful navigation of the technology.

Rodgers and Bremner (2019) argue that design has traditionally served as a nexus between art, science, and various other disciplines, advocating for a new approach to education, where creative practitioners are likened to modern-day travelers, navigating through a landscape of signs and formats. In this view, the emphasis shifts from reaching specific design destinations, or final objects, to elucidating the cognitive and critical practice of design thinking (Postlethwaite et al., 2019). By shifting our attention to the cognitive dimension of design, we can gain a deeper understanding of the mental processes and strategies employed by designers.

Specifically, regarding 3D fashion design, only very limited research has been conducted on the role of digitalization within the fashion industry (Arribas & Alfaro, 2018; Särmäkari, 2021; Noris et al., 2021). The majority of the limited research in 3D fashion design has predominantly focused on the technical capabilities of CAD and 3D simulation software (Sarakatsanos et al., 2021). Examples include exploring the industry advantages of 3D technologies for manufacturing fashion products like accessories, jewelry, and garments (Spahiu et al., 2021), as well as investigating various 3D printing methods and their applicability in fashion, alongside associated industry challenges (Yap & Yeong, 2014, Vanderploeg et al., 2016; Sun & Zhao, 2017). However, no attention has been given to the cognitive and learning processes central to fashion design, let alone in 3D simulation software. As such, the current scholarly landscape in fashion design offers ample opportunities to explore the praxis of fashion design as a cognitive endeavor and systematically document the knowledge of the discipline from a pedagogical standpoint. By formally capturing and archiving the cognitive manifestations of fashion design, we can enhance pedagogical practices and foster innovation within the field.

Purpose Statement

The aim of this study is to analyze, archive, and elucidate the cognition involved when creating in the virtual environment, utilizing four tenets relevant to design cognition of a novel framework, THREAD, with the objective of formally capturing the knowledge of the field of fashion design as cognitive praxis. In order to do so, the cognitive processes of undergraduate fashion students will be elucidated in interviews from engagement in capsule collection projects, specifically situated in the 3D software space. The findings will equip fashion design instructors with a more intimate understanding of fashion design thinking and learning as is situated in the increasingly pertinent 3D space, resulting in a unique opportunity to improve broader fashion design pedagogy and industry initiative. Student designers may also benefit from the findings of this study because it will provide them with an introspective lens from which they can reflect upon their own creative processes when designing in the 3D space.

Theoretical Framework

This qualitative study employs a novel theoretical framework of fashion thinking in the virtual fashion design learning environment, THREAD, to ground interview questions. The application of the THREAD model for this study will include the tenets relevant to design cognition for fashion thinking including: (1) creativity, (2) tacit knowledge, (3) visualization, and (4) haptic memory. Integrating this framework into the study design will help structure the research method and analysis, thereby enriching our understanding of design cognition, learning in virtual environments, and fashion design pedagogy.

Constructivist Paradigm

This study will be informed by the constructivist paradigm because constructivism emphasizes the subjective nature of reality, participant perspective, consideration of multiple realities, and the role of context in shaping meaning and experience (Piaget, 1967; Piaget, 1973; Dalgarno & Lee, 2009). Constructivism can be understood as a paradigm where knowledge is created by the reflexive process of actioning and responding to those actions by creating and adjusting dynamic knowledge structures (Piaget, 1967). It is known that the most transformative learning experiences, regardless of discipline, emerge from a learner's own curiosities and self-guided exploration (Kajamaa & Kumpulainen, 2019). Students glean more independence and agency in the virtual environment as compared to a traditional classroom setting as the instructor plays more of a role in content facilitation than in dispensing of knowledge and information (Bose, 2003; Goodyear et al., 2001; Parise, 2000; Smith et al., 2001). In this study, it is likely that students will learn in a proactive versus reactive manner, as their learning and cognition will take form and be revealed through a design project (Boynton, 2002). The constructivist paradigm is particularly suitable for grounding this qualitative study due to its emphasis on the active construction of knowledge through interaction with the environment.

According to Dalgarno and Lee (2009), the constructivist paradigm is well suited for grounding a study on thinking and learning in the 3D environment because the students will be able to construct a personal knowledge representation and iteratively undertake exploration and experimentation while refining their understanding. For example, it has been found that utilizing 3D technologies in physics education can enhance students' conceptual understanding by enabling the full physical behavior of objects to be modeled and observed, unlike traditional two-dimensional simulations (Chee & Hooi, 2023). Learning apparel design in 3D software mirrors the principles of constructivist learning, facilitating self-determination and sense of purpose through interest and the choice of what happens next in the learning environment. The capacity of 3D simulation software to provide content that is manipulable, and dynamic makes it uniquely suited to supporting student exercise of individual interest, resulting in a study centered on a constructivist learning approach. This study utilizes semi-structured interviews to go beyond just observing the tacit to uncovering the underlying cognitive mechanisms and the individual and contextual factors that shape learning, designing, and thinking in the virtual environment.

THREAD

The name "THREAD" for the theoretical framework in this qualitative study reflects a deliberate abstraction of the cognitive processes inherent in the fashion design learning environment. The term "THREAD" serves as a metaphorical representation of the interconnectedness and continuity of thought throughout the design process. Just as a thread is woven through fabric, connecting various fibers to form a cohesive whole, the cognitive processes represented by each tenet in the THREAD model thread through the designer's mind.

Each element of the THREAD framework symbolizes a different aspect of fashion thinking, contributing to the overall fabric of the design process. This study focuses on design cognition, of which 4 tenets are relevant including: (1) creativity, (2) tacit knowledge, (3) visualization, and (4) haptic memory. Creativity represents the initial spark of inspiration (Nielsen & Thurber, 2020), while tacit knowledge embodies the accumulated wisdom and expertise passed down through experience (Siu & Dilnot, 2001). Visualization enables the designer to transform abstract ideas into tangible forms (Chen & Golan, 2016), while haptic memory evokes the sensory experience of touch (Sun & Parsons, 2015), representing the physicality inherent in fashion design.

THREAD aims to abstract out the thread of fashion thinking, highlighting the interconnectedness and continuity of thought that underpins the fashion design process. This abstraction allows us to conceptualize design cognition in a holistic manner, recognizing the intricate web of mental processes that contribute to creative and innovative outcomes in the virtual fashion design learning environment. Utilizing THREAD's four relevant tenets (Table 4.1) as a conceptual framework will ground the study by offering a system for systematically analyzing the interview data by categorizing the data by the four tenets of design cognition for 3D fashion thinking. The model will aid in organization and interpretation of the data while providing a comprehensive model of the complex components of design thinking in 3D CLO for fashion design pedagogy. The following is a brief description of each of the four tenets and their application to the disciplinary context.

Table 4.1

THREAD *Framework of Fashion Thinking for 3D Design Pedagogy*

Proposed Tenet	Connection to Design Cognition	Connection to Fashion Design Pedagogy	Connection to learning 3D simulation software
Creativity	Creativity= key element of design process (Jackson, 2003)	generate ideas, solutions, and products that are novel and valuable (Sarkar & Chakrabarti, 2011).	3D simulation software plays critical role in creative exploration (Park et al., 2010).
Tacit Knowledge	"an intelligence expressing itself in other means than words" (Albers, 1944, p. 27).	Nearly all methods employed in fashion design require tacit knowledge (Sgro, 2018).	3D SS eradicates disconnect between making and design thinking (Siu & Dilnot, 2001).
Visualization	Visualization of science produces connection between seeing and knowing (Stafford, 1997)	Design ideas are communicated through visualization in all stages of the apparel design process.	3D simulation software for fashion design is a visualization tool, facilitating functional realism
Haptic Memory	Haptic memory= tactile consciousness, drawn from past experience working with physical objects	"thinking through the hand manipulating a material" (Nimkulrat, 2012, p. 64).	3D simulation software is a haptic-machine interaction system that is active & reconfigurable

Creativity

Creativity, a cornerstone of the THREAD model, is crucial in apparel design education, as emphasized by Black, Freeman, & Stumpo (2015), underscoring the need for tailored methods to foster creative behavior (Black et al., 2015). Creativity in fashion design involves generating novel and valuable ideas and solutions (Sarkar & Chakrabarti, 2011). In the 3D environment, creativity manifests as divergent thinking, enhancing artistic ability and demonstrated through fluency, flexibility, originality, and elaboration (Guilford, 1957; Nusbaum & Silvia, 2011). In CLO, apparel design fluency as a demonstration of creativity might look like the number of design ideas or iterations. Apparel design flexibility can be understood as the number of garment types and categories, or the range of conceptual ideas the student designer demonstrates. Elaboration in 3D fashion design might be witnessed as the amount of design detail executed, such as trim, functional closures, ease of donning/doffing, graphics and texture addition, and evidence of thinking through colorways. Originality will be identified as the uniqueness of design execution (Black et al., 2015).

Tacit Knowledge

Tacit knowledge, considered practical intelligence (Sternberg & Hedlund, 2002; Sternberg et al., 2000), involves self-extraction of knowledge from experience, context-specificity, and relevance to individual goals (Sternberg, 1997; Sternberg & Horvath, 1999; Sternberg et al., 1995; Sternberg et al., 2000). In the context of utilizing CLO for capsule collections, student designers' tacit knowledge may manifest as intuitive application of pattern drafting methods, domain-specific understanding of garment construction principles, or individualized design objectives. According to Siu and Dilnot, 3D computer technology presents a unique opportunity to re-contextualize the relationship of craftsmanship with a representational system in an artificial "making environment" (2001, p. 703). The disconnect between designing and making is essentially eradicated with use of 3D simulation software as the two processes occur simultaneously when developing a garment. 3D simulation software extracts the tacit knowledge by synchronizing the designer's mental and physical processes with making-techniques, craft-knowledge, and technical know-how (Siu & Dilnot, 2001).

Visualization

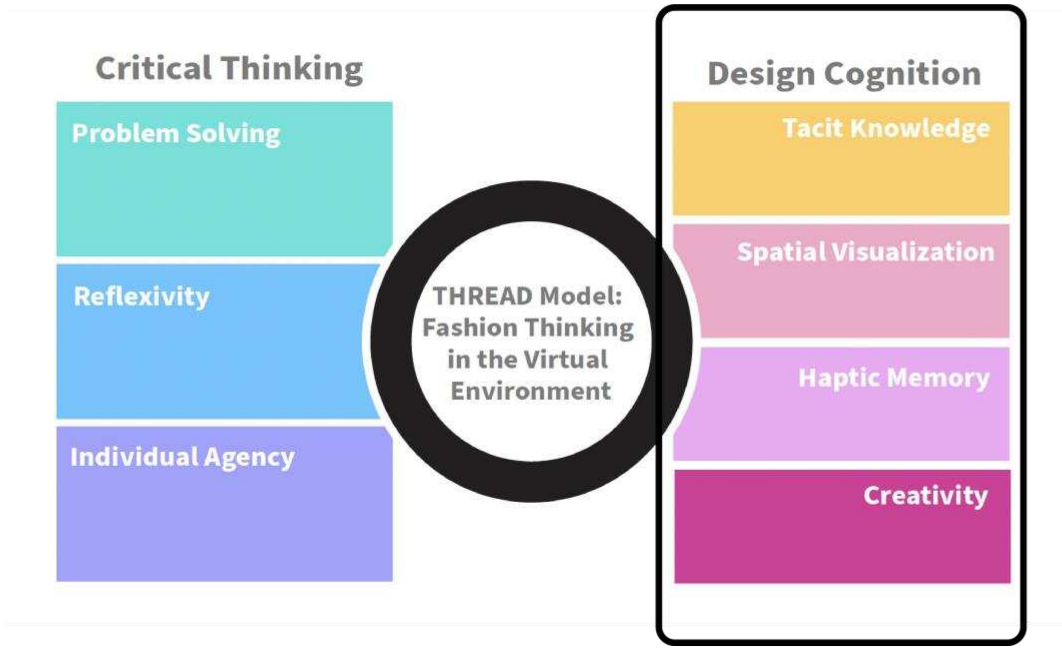
Visualization, crucial for understanding spatial relationships, is enhanced through 3D simulation software in fashion design, offering pragmatic, responsive, and realistic manipulation of digital representations (Power, 2013; Ferwerda, 2003). This enables designers to closely analyze details, test design iterations, and assess feasibility from functional, expressive, and aesthetic perspectives (Power, 2013; Ferwerda, 2003). Working in CLO, visualization involves manipulating virtual fabrics, textures, and colors to experiment with design elements and assess their impact on the overall garment appearance (Power, 2013; Ferwerda, 2003). Additionally, 3D simulation software integrates human-centric and machine-centric components, aiding in conceptual ideation and technical understanding (Chen & Golan, 2016; Hwang & Hahn, 2017). Through virtual prototyping, students improve visualization skills by analyzing on-body relationships and dynamic interactions with avatars (Park et al., 2010; Hwang & Hahn, 2017).

Haptic Memory

Haptic memory, an integral aspect of tactile consciousness, is deeply rooted in past experiences of interacting with physical objects and materials, guiding individuals' interactions with virtual textures and surfaces in 3D simulation software for fashion design (Nimkulrat, 2012; Carter, 2005). Haptic memory is closely tied to material thinking, which involves, "thinking through the hand manipulating a material" (Nimkulrat, 2012, p. 64). According to Carter (2005), materials are not mere passive tools to the maker but the means of embodiment with artistic intelligence that connects the mind to the hands and eyes.

Haptic memory is highly engaged when working with 3D simulation software. Haptic devices, such as 3D simulation software and its corresponding tools (3D mouse, tablet, stylus pen) rely on the force feedback concept, where the output device transmits pressure, force, or vibrations to enable the user to sense change in the virtual environment (Blade & Padgett, 2002).

When working in CLO to design a capsule fashion collection, engagement of haptic memory may look like a) drawing upon memories of how different materials feel and behave in real life when sculpting virtual fabric or manipulating digital textures and b) gauging the resistance,



texture, and responsiveness of the CLO interface and its tools.

Figure 4.1

Graphic Representation of the THREAD Model (Design Cognition Focus)

By incorporating the seven tenets of critical design cognition, the THREAD framework serves as a valuable tool in abstracting out the thread of cognition inherent in 3D fashion design and provides a lens through which to identify and understand the diverse cognitive methodologies employed by designers. Each tenet illuminates a distinct aspect of the design process, from creativity and tacit knowledge to reflexivity and haptic memory, contributing to a holistic understanding of how designers navigate the complexities of virtual fashion design. Through the THREAD framework, we can discern the intricate threads of thought woven throughout the design process, highlighting the nuanced ways in which designers engage with and manipulate digital tools to bring their creative visions to life.

Literature Review

Fashion design cognition in the virtual space is situated as a complex and intersectional subject. As such, it requires a comprehensive exploration of various interconnected areas of study that collectively shape the design process including a) the fashion design thinking process, b) generalized design cognition as it is situated in the virtual environment, c) design thinking, d) problem-solving in design, e) design thinking in 3D, f) spatial visualization, g) realism, h) creativity, i) industrial considerations of 3D simulation software, j) and knowledge transfer.

First and foremost, delving into the intricacies of the fashion design thinking process provides crucial insights into how designers conceptualize, iterate, and realize their creative visions. Additionally, considering generalized design cognition within the virtual environment discusses how digital tools and platforms influence the cognitive processes inherent in design. Exploring design thinking and problem-solving in design sheds light on the methodologies employed by designers to address challenges and generate innovative solutions, particularly in the context of 3D simulation software. The integration of design thinking principles into 3D environments considers how spatial visualization and realism impact the design process. Furthermore, examining creativity as a fundamental aspect of design cognition elucidates the role of ingenuity in shaping virtual fashion praxis. Industrial considerations surrounding 3D simulation software, including its technological capabilities and limitations, provide valuable context for understanding its implications for fashion design pedagogy and practice. Finally, exploring knowledge transfer mechanisms facilitates the dissemination of expertise and insights within the design community, fostering collaboration and innovation in virtual fashion design endeavors. Through an interdisciplinary lens encompassing these intersecting subjects, this literature review aims to enact a preliminary understanding of fashion design cognition in the virtual space.

Fashion Thinking

The thinking process in fashion design study is largely constructed of nonverbal ways of knowing and communication (Entwistle, 2000; Raebild, 2015, Petreca, 2017; Vangkilde, 2017; Atkinson, 2017), such as drawing, technical CAD sketches, 3D modeling, flat patterning, and draping. The process of making through the nonverbal methods listed serves as a record of ideas, aid to internal thought, conceptualization of preliminary thought, development of inspiration and a log of dynamic design (Braddock et al., 2012). This cognitive process moves between two-dimensional and three-dimensional form. First, the concept emerges in 2D form through croquis sketching, color palette development, flat patterning, and mood/fabrication exploration. Then, the designer moves to 3D to speculate feasibility and to test silhouette, drape, and construction methods. In an iterative process, the designer moves back and forth from 2D to 3D, in a process where the initial design evolves and emerges through modification in each form (Gully, 2010).

The process centers on enmeshment of the designed artifact and the thought process, as described by Gully (2010):

> Design knowledge resides as much in the processes as it does in the product; the strategies of designing reveal the intimacies of thought, while the design knowledge that resides in the product itself- the garment- is an embodiment of the process (p. 41).

The speculative garment and broader collection will certainly change and evolve in response to a dynamic design process that is informed, responsive, and moves from 2D to 3D. It has been proposed that designers are engaged in three reflexive conversations with the artifact that are interchangeable, continuous, and nonlinear. One conversation occurs in the designer's mind and shapes the imagined object while the other two conversations center on the 2D development (sketching and patternmaking) and the 3D representation of the design (3D simulation or draped physical garment) (Gully, 2010). It is imperative that students engage with the design process with a certain awareness in order to encourage development of meaningful meta-cognition. The fashion design process, whether situated in academia or industry, can be accurately described as a series of decisions regarding color, fabrication, silhouette, and functionality.

Past research on the cognitive process of fashion design centers primarily on sketching, underscoring the multifaceted roles these drawings fulfill within the broader design process (Culpepper, 2013). Fashion designers' sketches have been identified as reflections of design cognition (Scrivener et al., 2000), fostering creativity (Cham & Yang, 2005), initiating dialogue (Goldschmidt, 2003), storing ideas (Cham & Yang, 2005), and prompting innovation (Goldschmidt & Smolkov, 2004). 3D renders serve as digital analogs to traditional sketches for fashion designers, offering a dynamic platform that deeply engages their cognitive processes. Much like sketching on paper, creating 3D renders requires designers to visualize and conceptualize their ideas, translating mental images into tangible forms. Just as sketching enables designers to explore various design iterations and refine their ideas, 3D simulation software provides a versatile environment for brainstorming and problem-solving.

Design Cognition and the Virtual Environment

In the teaching and learning context, 3D simulation software is also referred to as the 3D virtual learning environments and photorealistic 3D modeling. In a general sense, a 3D virtual learning environment can be understood as a setting that, "capitalizes upon natural aspects of human perception by extending visual information in three spatial dimensions" that "enables the user to interact with the displayed data" (Wann & Mon-Williams, 1996, p. 833). Teaching and learning studies have found that when students engage content in a 3D virtual learning environment, improvements are seen in spatial knowledge representation, motivation and engagement, learning contextualization, and collaboration (Dalgarno & Lee, 2010). One of the potential benefits of utilizing realistic 3D modeling for learning is an increase in spatial understanding, which can be explained by the Geon Theory.

The Geon Theory, which was proposed by Biederman in 1985, purports that the Geon is a basic perceptual element used to process and organize visual stimuli. Such units may include 3D shapes and meshes including cones and cubes, and it is this process of cognitively grouping Geons as primitive 3D shapes that improves the learner's spatial cognition (Biederman, 1985). Kavakli explains the role of Geons in conceptual design, "part by part externalization of objects may be a characteristic feature of sketching activity… …the basic structural parts of an object (as denoted by Geon-like volumetric primitives)" (Kavakli et al., 1998, p. 490). Mukerjee and Muley (2004) describe that conceptual design, regardless of discipline, maintains the hallmark of vagueness until the design is completely developed. The geonic theory permits the designer considerable flexibility. 3D simulation software is congruent with the designer's need for flexibility as it permits a constructivist learning environment, where the learner refines and creates knowledge in a participatory manner (Lee et al., 2021). Studies have shown that in a constructivist virtual environment, students demonstrate an improvement in agency and independence (Bose, 2003; Goodyear et al., 2001; Parise, 2000; Smith et al., 2001). Pande and Bharathi (2020) Demonstrate that a constructivist approach to teaching design thinking results in the strengthening of students' thinking and retention capabilities.

Design Thinking

In generalized art and visual design, design thinking is regarded as an interdisciplinary theory for understanding art by embracing the balance of creative problem solving, aesthetics, and conceptual practice (Davis, 1999). Brown (2009) defines design thinking as, "a discipline that uses the designer's sensibility and methods to match people's needs with what is technologically feasible and what a viable business strategy can convert into customer value and market opportunity" (p.86). The objective of design thinking is to nurture a growth mindset where innovation is the key to overcoming future and current industry challenges (Brown & Kātz, 2019). Design thinking is described as reflection in action, and it is one of the most integral skills the design student will learn (Bailey, 2010). According to Bailey (2010), unpacking the meaning and application of design thinking is valuable because it helps us identify a new focus for contemporary apparel design curriculum. Encouraging students to engage in reflection during the design process may enable them to deviate from habitual methods, engender flexibility in thinking and process, and develop more divergent design work (Mezirow, 1991). According to Coorey (2012), the ability to reflect on your own learning and work, and to adjust in action, has been identified as one of the key determinants of successful design thinking.

It is important to discuss design thinking in a study that aims to elucidate cognition in 3D fashion design because design thinking offers a structured approach that emphasizes empathy, ideation, prototyping, and iteration, all of which are integral components of the creative process in fashion design. By exploring design thinking alongside cognition, researchers can gain insights into how designers utilize cognitive processes to generate ideas, solve problems, and make decisions within the context of 3D design. Just as "design" can refer to both a noun and a verb, "fashion" also encompasses dual meanings. Given that design thinking emphasizes the inseparability of cognition and action, fashion can similarly be seen as an amalgamation of both design and cognition (Julier, 2013). In other words, the process of fashion creation involves not only conceptualizing and planning (design) but also implementing and expressing ideas (action), blurring the lines between thought and execution (Saariluoma et al., 2021). Therefore, viewing fashion through the lens of design thinking underscores its dynamic nature, highlighting how cognitive processes inform and shape the tangible outcomes in the realm of fashion design. Understanding how design thinking manifests as and intersects with cognitive processes in 3D can enhance our comprehension of the design process in this virtual realm.

When engaging design thinking, the focus is on creative and practical thinking processes, where the student is encouraged to seek ways to meet human need through design (Diachent, 2010). Design thinking pedagogy develops students' intuitive analytics, which hinge on the ability to combine ideas, analysis, and problem solving, which helps to bridge the gap between subjective and objective and integrates aesthetics with technicality (Kellogg, 2006). One study found that when design thinking practices are embraced in the art and design classroom, students' quality of creativity is improved (Ingalls Vanada, 2014). Understanding the role of design thinking in the larger cognitive process is essential as it provides insights into how designers approach problem-solving, creativity, and user-centric design.

Problem Solving in Design

Fashion design involves addressing various design challenges, from conceptualizing innovative solutions to addressing technical issues in garment construction and assembly. Thomke and Fujimoto (2000, p.130), describe product design as a series of problem-solving cycles starting with "problem recognition and goal definition" where the designer progresses through experimental exploration of alternatives. According to Oh and Jonassen (2007), problem solving encompasses three stages to include: (1) transformation, (2) clarification, and

(3) implication. In the clarification stage, the challenges are formulated, and the overall vision is explored (Puccio et al., 2004). The last stage consists of the designer creating a plan and assessing the solution (Puccio et al., 2004). It is necessary to understand the mechanisms of problem-solving, as it is an integral component of the larger cognitive process innate to designing within 3D simulation software.

Design Thinking in 3D

The nature of the fashion design thinking process can be accurately described as, "an activity involving reflective practice" (Dorst, 2003, p.4). This reflective practice is inherent because design problems are uncertain, and the solution is often discovered within the process. In engineering design, it has been found that when using a 3D CAD simulation tool, students showed improvement in (a) understanding the design challenge and (b) building knowledge, both tenets of design thinking (Taleyarkhan et al., 2018). Design thinking is promoted by 3D CAD because the software provides students an opportunity to evaluate many different design alternatives and to test iterations quickly and efficiently (Taleyarkhan et al., 2018). While Taleyarkhan et al. (2018) found that 3D CAD facilitates development of alternative design iterations, other engineering literature shows that simulation software promotes idea fluency (Goldstein et al., 2015), experimentation (Vieira et al., 2016), and iteration of solutions (Crismond & Adams, 2012). Evidence exists that simulations promote design thinking because they encourage students to, "visualize and experiment with otherwise inaccessible phenomena." (Horwitz & Barowy, 1994, p. 1).

Spatial Visualization. Spatial visualization is inherent to design thinking as it involves the mental manipulation and representation of three-dimensional objects and spaces, allowing designers to envision and conceptualize ideas, visualize design concepts from multiple perspectives, and assess spatial relationships and proportions. For example, in the area of game design, it was found that design thinking techniques enhance the immersion experienced when engaging visualization skills (Wanick et al., 2019).

Spatial visualization can be described as the ability to cognitively manipulate the complex relationship between 3D object with space through an understanding the relationship of elements relative to each other (Salthouse et al., 1990). The mental manipulation of objects demonstrated by the engagement of spatial visualization skills has shown to be very valuable in a plethora of fields including architecture, engineering, and mathematics (Chen, 2004; Braukmann, 1991; Lowrie et al., 2019; Strong & Smith, 2002). Two factors, visualization, and orientation, demonstrate the concept of spatial visualization (McGee, 1979). In the context of apparel design, patternmaking requires that the designer engages both visualization and orientation skills when manipulating and analyzing the 2D patterns in anticipation of the shape of the 3D garment. In fashion design, patternmakers must seamlessly transform 2D patterns to 3D garments through an understanding of how adjustments, such as dart position or seam manipulation, will affect the 3D outcome. As such, visualization is likely an important component of design thinking to consider in the 3D design environment.

Realism. Realism is a key component of visualization. It has been shown that the more realistic a visual learning environment is, the better the learner can immerse and engage (Dede, 2009). Compounding this engagement and motivation produced by heightened realism is a mirrored increase in the learner's emotional response. When engaging in highly realistic learning environments, viewers affective states intensify, influencing the selection, organization, and integration of learning into new mental models (Nebel et al., 2020). Studies that utilize eye-tracking technology to assess learning attention show that more detailed imagery produces better attention and memory stimulation in both the initial learning phase and overall learning experience than simple illustration (Lin et al., 2017). The creative process is closely linked with realistic representation, highlighting the importance of 3D CAD due to its strong representational capabilities (Abdel-fattah et al., 2012; Augello et al., 2013; Cölln et al., 2012).

Industrial Considerations of 3D Simulation Software

The capabilities of 3D simulation software essentially promote the bypassing of the divergent stage as the software is so intricate that the designer is enabled to immediately scrutinize design detail. This is referred to as front loading, which is, "a strategy that seeks to improve development performance by shifting the identification and solving of [design] problems to earlier phases of a product development process" (Thomke & Fujimoto, 2000, p. 129). While this may seem like a positive, the negative aspect is that eliminating the divergent portion of the design process essentially shortcuts the early phases and may actually increase time and cost in the long run (Fixson & Marion, 2012). It is a possibility that ruling out the divergent stage in the product design process fosters the ability to adjust the virtual garment very late in the prototyping cycle, which may eventually erode design discipline by presenting opportunity to adjust patterns and grading very late in the cycle (Fixson & Marion, 2012).

In product development, both thought models are important, yet 3D CAD fosters an environment for only the convergent, technical problem-solving mechanism. According to Fixson and Marion (2012), it is unclear whether this focus on technical problem-solving and convergent thinking will be beneficial on a larger scale. Thus, it's important to attempt to understand design cognition in the pedagogical 3D environment. With a solid divergent process where many solutions are explored, and the initial framing of the problem is thorough, fewer prototypes and convergent thought may be required later on (Fixson & Marion, 2012). As long as designers can ensure that the front-loading of the design process does not result in pushing divergent thought and essential design structure into the convergent phase, 3D CAD has the unique ability to inform new methods of thinking about design problems.

Knowledge Transfer

In both traditional paper and pencil and 3D fashion design, the design process centers on an articulation of tacit, abstracted, and conceptual knowledge to explicit translation as the product moves from conceptual design to physical prototype. The findings from one study suggest that in the transforming product development and fashion industry, one of the main keys to operational success lies in organizational tacit knowledge creation, sharing, and integration (Nonaka & Takeuchi, 1995). According to Siu and Dilnot (2001), 3D computer technology presents a unique opportunity to re-contextualize the relationship of craftsmanship with a representational system in an artificial “making environment” (p. 703). The disconnect between designing and thinking is essentially eradicated with use of 3D simulation software as the two processes occur simultaneously when developing a garment. In the information systems field, one study found that 3D simulation technologies significantly improve the organizational knowledge creation process and in turn, this improvement leads to advancement in streamlining the product development process (Yap et al., 2003). Regardless of design discipline, 3D simulation software effectively captures tacit knowledge and expands the users’ cognition through visual perception.

As the fashion design discipline transforms from the physical garment as the primary objective to a more expansive focus on process and cognition, it is important to document the cognitive design process. The growing need for design process inquiry is arguably even more paramount in the virtual space, as literacy in 3D design methodology becomes an increasingly essential skill in the fashion industry.

Methodology

This study aimed to analyze, archive, and elucidate the cognition involved when designing in the 3D environment, by utilizing the THREAD framework to formally capture the knowledge of the field of fashion design as cognitive praxis. In order to investigate design cognition in the 3D fashion design process, qualitative interview data was aligned with the relevant four tenets of design cognition within the THREAD model of fashion thinking. Qualitative methodology was deemed to be well-suited for this study because qualitative methods allow for in-depth exploration and understanding of participants' experiences, perceptions, and behaviors, which is essential for examining complex phenomena such as cognition in a design context. This approach fostered rich and detailed responses that provided insights into the complexities of learning and cognition within this context. By engaging participants in semi-structured interviews, the research delved into the nuances of apparel design learning and cognition, capturing the intricacies of how individuals navigate and make meaning of the novel virtual design environment. This allowed for a nuanced understanding of the cognitive processes, strategies, and challenges involved in virtual apparel design.

Qualitative interview methodology also provides an opportunity for adaptation and probing based on participants' responses, uncovering unexpected insights, and addressing emerging themes. The iterative process innate to qualitative research ensured that the study remained responsive to participants' perspectives and experiences, enhancing the validity and richness of the findings. Qualitative research allows for flexibility and adaptability in data collection and analysis, enabling the exploration of emergent themes and patterns in the data.

This approach aligns well with the dynamic and iterative nature of design processes, where creativity and problem-solving skills are central. The methodological design of this study hinged on a naturalistic inquiry approach where one on one artifact interviews were held to elucidate the cognition of participants when designing in 3D simulation software.

Study Environment

The environment for this study was 2 senior undergraduate fashion design capsule courses where CLO 3D was a method of design required for the final outcome. Capsule in this context means that the courses centered on a mini project or final collection. In both courses, the researcher was the instructor. The first course was entitled Technical Studio III and focused on 2D and 3D iterations, the digital sampling process, and the use of 3D simulation software (CLO) to ideate, draft patterns, drape, fit, and present final design collections. The second course, Senior Thesis Collection, centered on the actualization of senior fashion design students' capsule collections, which were required to be presented in 3D form.

Before beginning these courses, students had already completed projects and modules in 3D CLO in prerequisite courses that demonstrated their competence in the software. The courses sampled were offered once a year in the fall term (both A and B sections) and the structure required that students entered the class with existing proficiency at an intermediate level in 3D simulation software in order to successfully actualize 3D renders of their designed garments in a final capsule collection project. The courses were required for fashion design students' completion of their degree program, and both were comprised of junior and senior students.

The researcher classified and estimated participants' comfort levels, expertise levels, and years of experience in CLO 3D based on multiple factors, including their previous work in CLO 3D within the two courses sampled, their academic standing and course progression at the college, and their perceived familiarity and confidence with the software during data collection. The 1-5 comfort level ratings were determined based on a combination of students' perceived confidence in CLO 3D, their observed proficiency in coursework, and the complexity of tasks they were able to execute independently. A rating of 1 indicated minimal comfort with the software, while 5 represented a high degree of ease and fluency in navigating CLO 3D for advanced tasks such as virtual draping, pattern manipulation, and rendering. Students who demonstrated strong command of CLO 3D tools, worked efficiently with little instructor guidance, and expressed high confidence in their abilities were rated at the higher end of the scale (4-5). Those who required more troubleshooting or expressed hesitancy in executing complex tasks were rated lower (2-3).

The beginner, intermediate, and advanced expertise levels were assigned based on a combination of students' years of experience and their demonstrated ability to handle CLO 3D functions at increasing levels of complexity. Given that all students in these courses had completed prerequisite CLO 3D coursework, none were classified as beginners. Instead, intermediate students were those who had 1-2 years of experience and demonstrated competence in fundamental CLO 3D functions (e.g., basic pattern manipulation, garment construction, and simulation). Advanced students had either 3+ years of experience or exhibited strong technical proficiency in executing complex tasks such as multi-layered garment simulations, advanced material applications, and integrating CLO 3D into their broader design workflows with minimal guidance.

Since enrollment in these upper-level courses required prior successful completion of prerequisite CLO 3D projects and modules, all students were expected to have at least an intermediate level of proficiency before beginning the course. However, individual comfort levels still varied, ranging from 3 (moderately comfortable) to 5 (very comfortable), as shown in Table 4.2. Demographic data was not collected.

It was logical to conduct a study exploring 3D simulation software and student designers' design cognition within the context of upper-class undergraduate fashion courses for several reasons. Firstly, the course structure, which required that students in the course already had an intermediate understanding and ability in 3D, provided a conducive environment for studying the software's influence on cognition. Additionally, the course's emphasis on the creation of a collection (senior capstone or capsule) project highlighted the practical relevance of the study, as these are activities that closely mirror real-world design scenarios. Moreover, the courses' statuses as foundational for junior and senior fashion design students underscored the importance of understanding the interaction between 3D simulation software and design cognition, as it directly related to students' preparation for their future careers in the fashion industry.

Table 4.2

Participants' Comfort Level, Expertise, and Experience in CLO 3D

Student ID	Comfort Level (1-5)	Expertise Level	Years of Experience with CLO 3D
S1	4	Intermediate	1-2 years
S2	4	Intermediate	1-2 years
S3	3	Intermediate	1-2 years
S4	4	Intermediate	2 years
S5	3	Intermediate	1-2 years
S6	5	Advanced	3+ years

Student ID	Comfort Level (1-5)	Expertise Level	Years of Experience with CLO 3D
S7	5	Advanced	1-2 years
S8	3	Intermediate	1 year
S9	4	Intermediate	1-2 years

CLO 3D

CLO 3D is a 3D simulation software program. 3D simulation software in fashion design centers on providing a platform where the user can pattern-make, design, and render virtual garment prototypes. Essentially, virtual means digital, which denotes that the process is occurring on a computer or computer network (Mitra, 2003). The software enables the designer to prototype all angles and details of the virtual garment and to even render out photorealistic imagery that can be seamlessly incorporated in tech packs, product line management systems, and even as online representations of product. 3D simulation software provides a singular environment for patternmakers to draft the patterns, stitch them together in the corresponding 2D window and then position the pattern pieces correctly around 3D avatars for the eventual simulation of the garment on the form, producing a high-resolution image referred to as a render (Baytar, 2018). With 3D CLO, designers can create virtual garments with remarkable realism, allowing for detailed visualization and manipulation of fabric drape, texture, and fit. The software enables seamless transition from initial concept to final product, streamlining the entire design process.

Participants

The study adopted a convenience sampling approach, where all interested participants from two classes comprising a total of 17 students were included in the study (Wienclaw, 2019). The interested participants totaled 9 and this was enough to reach saturation. The convenience sample, which is the most common sampling method employed in qualitative research, is defined as the collection of data from whoever is willing to participate in a study, is the most approachable, or the most conveniently accessible to the researcher (Wienclaw, 2019). Participants were recruited through a portal e-mail letter administered to all students in each course by the instructor. All students were granted 10 points extra credit for participation in the interview. An alternative activity was created and managed by the instructor of the course for students who still wished for extra credit but did not want to participate in the study.

The sample was 9 students who were interested in participating from a group of 17 in two upper-class courses involving 3D simulation software situated in a fashion design department within a Western 4-year college. Selection criteria included having taken 1) all required prerequisites for the course sampled, which demonstrated adequate proficiency and experience in the software, 2) at least three years of training in hands-on patternmaking, apparel construction, and/or sewing, and 3) experience in application of 3D simulation software knowledge to final product development or rapid prototyping. The course prerequisites and structure ensured that all selection criteria was met simply by being a student in the course, hence the convenience sampling approach.

Conversely, exclusion criteria involved inexperience with 3D software. Demographic details included: 1) fashion design specific degree specialization, 2) final two-year stage academic degree progression, 4) technological proficiency, and 5) interest in fashion design and 3D technology to ensure a comprehensive participant pool. The demographics listed aligned with the course sampled as the class included junior and senior level fashion design students with a background of coursework in 3D simulation software and patternmaking, with the same proficiency in 3D software considering the academic stage of progression. The selection process described aimed to ensure that participants possessed the requisite background and expertise to offer valuable insights into design cognition within the virtual environment. With all interested participants included in the study, the research questions were effectively explored, and the data collected from 9 students reached saturation.

Interview Method

In the general design field, the interview method has a proven record of usefulness in researching the creative process (Ambrose et al, 2003; Csikszentmihalyi, 1996; Gardner, 1993). The qualitative interview method made sense for this study because of the emphasis of subjective construction of knowledge and meaning by individuals. In the constructivist view, knowledge is not passively received but actively constructed by learners through their interactions with the environment. By conducting interviews, the researcher explored how student designers interact with and navigate the 3D environment, gaining insights into their thought processes, problem-solving strategies, and conceptual understandings. This method enabled a comprehensive exploration of participants' cognitive engagement with the 3D environment, including how they conceptualized and manipulated objects, visualized spatial relationships, and addressed challenges. Interviews were selected as a suitable method for investigating the design cognition side of fashion thinking because they provided a platform for participants to reflect on and articulate their tacit knowledge, spatial visualization skills, and creative processes. These elements of design cognition are often deeply embedded in prior physical experiences, which may not emerge as clearly in real-time observations. Interviews allowed for deeper exploration of these embodied and intuitive aspects, offering participants the opportunity to explain how they mentally map physical techniques onto virtual workflows. Additionally, the interview method created space for discussing long-term experiences, cultural influences, and personal motivations that shaped participants' cognitive approaches to fashion design. Just as qualitative interviews have provided rich insights into students' understanding in physics education by probing their experiences with 3D simulations, they similarly illuminated the nuances of cognition in the 3D environment in apparel design.

The interview protocol, developed to explore the research question, “what does apparel design learning and cognition look like when the process is actualized in the virtual environment?” followed the format of the THREAD model. The interview protocol was built from a predetermined set of questions, organized by four relevant tenets of the THREAD framework, and remained open to reform, addition, and follow-up questions, as suggested by Glesne (2011). Additionally, interviews revolved around artifacts in two forms including the designed capsule collection 3D renders and the sketches completed as a supplement to cognition during the interview.

The interview questions (Appendix) covered each of the four domains of design cognition inquiry in the THREAD model, including (1) creativity, (2) tacit knowledge, (3) visualization, and (4) haptic memory. Each of the four domains of inquiry were targeted by 3 to 5 questions, but none of the interviews remained completely within the established questions, which created space for spontaneity and flow. In this way, the framework of questions (Appendix) guided the inquiry, but the interviewee and interviewer were granted the freedom to diverge and explore the topic more deeply, providing opportunity to delve into unanticipated areas of interest. The questions were open-ended, prompting the participants to discuss their thinking in their own words (van Manen, 1990). Participants were asked about their design cognition as it aligns with each tenet of the THREAD model when working in 3D software. For example, to elucidate the participants’ engagement of spatial visualization skills, the following question was asked: “How did your experience with physical three-dimensional toiles impact your utilization of the 3D simulation software?" Probing questions were utilized as follow-ups to encourage student designers to provide additional information.

Data Collection

The interview sessions were held on zoom, where they were digitally recorded and later transcribed using Adobe Premier Pro. A copy of the interview questions was included in the chat feature of the Zoom interviews, so that participants could read along as questions were being asked, reducing cognitive load. The identity of participants was kept anonymous in the interview data, which was established with the participants before the commencement of data collection protocol.

Conducting interviews on Zoom offered several advantages for the study. Zoom provided a convenient platform for remote interviews, allowing participants to engage in the study from any location with internet access, thus increasing accessibility and participation rates (Howlett, 2021). Conducting interviews online offered the advantage of allowing interviewees to remain in their familiar environments, where they could easily access resources, share artifacts or demonstrations, and exchange digital materials such as documents, photos, and videos in real-time (Van Zeeland et al., 2021). This benefit was especially applicable for this study, which hinged on the artifacts of 3D renders and sketches. This flexibility enhanced the interview process and promoted a richer exchange of information and insights between the interviewer and the interviewees, as noted in studies by Bryman (2016) and Lo Iacono, Symonds, and Brown. (2016). Overall, leveraging Zoom for interviews enhanced the efficiency and effectiveness of data collection while prioritizing participant comfort and accessibility in the research process.

Participants were encouraged to open up the .zprj file in 3D CLO during the interview to help stimulate insight and reflection on their design process. This strategy also helped some interviewees to explain 3D modeling processes through action by way of screen-sharing, as implicit design thinking is often difficult to verbalize. In this stage, interviewees were encouraged to pull out any sketches or digital inspiration which was utilized when designing in CLO or surfaced during the course of the interview. Both the screen-sharing and sketches were additional tools to prompt elucidative discussion of the visual and implicit knowledge present in the virtual design process elucidated by the artifact interviews.

Artifacts in Design

The interviews revolved around artifacts in two forms including the designed capsule collection 3D renders and the sketches. According to Heylighen and Nijs (2014), designed artifacts act as a scaffold to the emergence, development, and transfer of individual cognition. In this study, the sketches and recordings acted as epistemic objects, within which knowledge was imbedded and inscribed, and as phenomenological agents of the cognitive design process. In a digital format, participants were encouraged to utilize digital sketching tools or software, such as Procreate, to create sketches of any concept or image-based ideas that emerged during the interview. They were encouraged to share their screens to display their sketches in real-time, allowing for immediate discussion and analysis. Alternatively, participants were also directed that they may use a pen and paper to sketch their ideas physically and then hold their sketches up to the camera for the interviewer to see. These sketching methods facilitated visual exploration and enhanced the discussion of visual and implicit knowledge inherent in the virtual design process, in a remote interview setting. In order to study design cognition in the novel virtual design environment, it was necessary to prompt conversation of artifacts as they exist within the physical structure of 3D space.

Pilot Interview

A pilot of the semi-structured interview methodology was conducted with a recent graduate who was very familiar with 3D CLO and utilizes the software as a component of her contract job at a Fortune 500 fashion company. This candidate was chosen because as a recent graduate, she had experience using 3D simulation software in both her academic and professional experience. This made her a uniquely suitable candidate to provide valuable insight and feedback on whether the interview protocol was clear, comprehensive, and conducive to eliciting meaningful responses from students. This pilot interview permitted the identification of potential flaws or ambiguities in the protocol before conducting the main study. The pilot ensured that the interview questions were clear, understandable, and conducive to capturing design cognition. Piloting the protocol created space for refinement and fine-tuning of the interview questions and method, optimizing the study's validity and reliability

Transcription

Each of the personal interviews was recorded and conducted utilizing zoom and immediately transcribed using Adobe Premiere Pro software. A transcript is a "written verbatim word-for-word account of verbal interaction, such as an interview or conversation" (Gale et al., 2013, p. 2). A transcription key was included to assess tone, which conveyed meaning beyond words (Bird, 2005). In order to properly analyze and understand the interview data later on, voice inflections, sarcasm, surprise, and hesitation, among many other tones were noted. In an effort to preserve data meaning, maintain response depth, and to offer room for interpretation and analysis, transcribing tone was an integral component of the methodology (Lapadat & Lindsay, 1991). As this research had the potential to inspire sensitive subjects, pseudonyms were utilized in transcription, as advised by Glesne (2011). The interviewee's real names were utilized until all data was collected, and then they were transferred to pseudonyms in transcription. Despite the use of pseudonyms in transcription, participants were referred to collectively as "student" in the findings. This decision stemmed from the study's focus, which did not aim to differentiate between individual participants or analyze variations in their responses. Instead, the data was presented as representing a homogeneous group, emphasizing shared experiences and patterns rather than individual distinctions. Additionally, transcripts had large margins and adequate line spacing for coding and notes (Gale et al., 2013).

Methods for Data Interpretation

After conducting the semi-structured interviews, the collected data was analyzed thematically by the identification of patterns and common themes tying back to the THREAD framework. According to Gale et al. (2013), an analytical framework, which in this study was the THREAD model, is a "set of codes organized into categories that have been jointly developed by researchers involved in analysis that can be used to manage and organize the data" which was employed to summarize and reduce the data to answer research questions (p. 1471). The framework method of analysis is most commonly utilized for thematic analysis of semi-structured interview transcripts, hence its relevance in this study (Pope et al., 2000). Analysis of the artifact interview data involved a thematic approach in an attempt to understand underlying meanings and messages conveyed by the cognitive patterns identified. The overarching categories were defined as clusters of codes, which were understood as descriptive or conceptual labels assigned to excerpts of raw data (Gale et al., 2013). Saldaña describes codes as, "a word or short phrase that symbolically assigns summative, salient, essence capturing, and evocative attribute for a portion of language-based or visual data" (2021, p. 5).

Coding Process

Saldaña (2016) informed the structure and process of coding the data and provided valuable guidance for analyzing qualitative data in research endeavors, hence its value as a resource in this study. Specifically, the two-part coding cycle was instrumental in organizing and analyzing interview data obtained from undergraduate fashion design students utilizing 3D simulation software to create capsule collections (Saldaña, 2016). Saldaña's suggestion of delving into methods relating to themes, was particularly relevant for tying codes back to the developed THREAD model, which encompasses four design cognition tenets for virtual design, including creativity, tacit knowledge, visualization, and haptic memory (2016). As seen in Figure 4.2, codes were grouped into categories that are similar and interrelated, in an effort to begin to abstract out the raw data. The process began with an overview of the data. Each data set was reviewed in its entirety to understand its context and meaning, with initial notes capturing salient phrases, action descriptions, and sentences. Each new set of data was analyzed individually while ensuring consistency across all sets. Salient portions were segmented into meaningful units and assigned to specific codes derived from both deductive and inductive approaches. The first round of coding focused on descriptive and initial observations, laying the groundwork for subsequent analysis. In the second round, a deductive coding approach was applied, aligning segments of data with the THREAD framework, specifically focusing on design cognition dualities such as tacit knowledge, spatial visualization, haptic memory, and creativity. This structured approach ensured that the 4 foundational elements of the framework were systematically integrated into the analysis. During the third round, an inductive approach was employed, enabling the identification of emerging themes. Phrases that did not initially align with the THREAD framework were grouped and explored to uncover additional patterns and themes and sub-codes were created under each initial code. The fourth round involved reflecting on and refining the codes across all data sets, ensuring that they accurately represented the data's content and meaning. This step also helped ensure consistency across the nine data sets, allowing for a more cohesive analysis. In the fifth round, all coded data were compiled into a single document where codes and sub-codes were organized under the THREAD framework, with corresponding analyses and relevant quotations included. This stage involved scrubbing the data for inconsistencies, overlaps, and any ambiguities. Finally, in the sixth round, a holistic review of all data sets was conducted. The final refinement process expanded and reorganized codes to create a comprehensive and nuanced understanding of the data in relation to the THREAD framework (Figure 4.2).

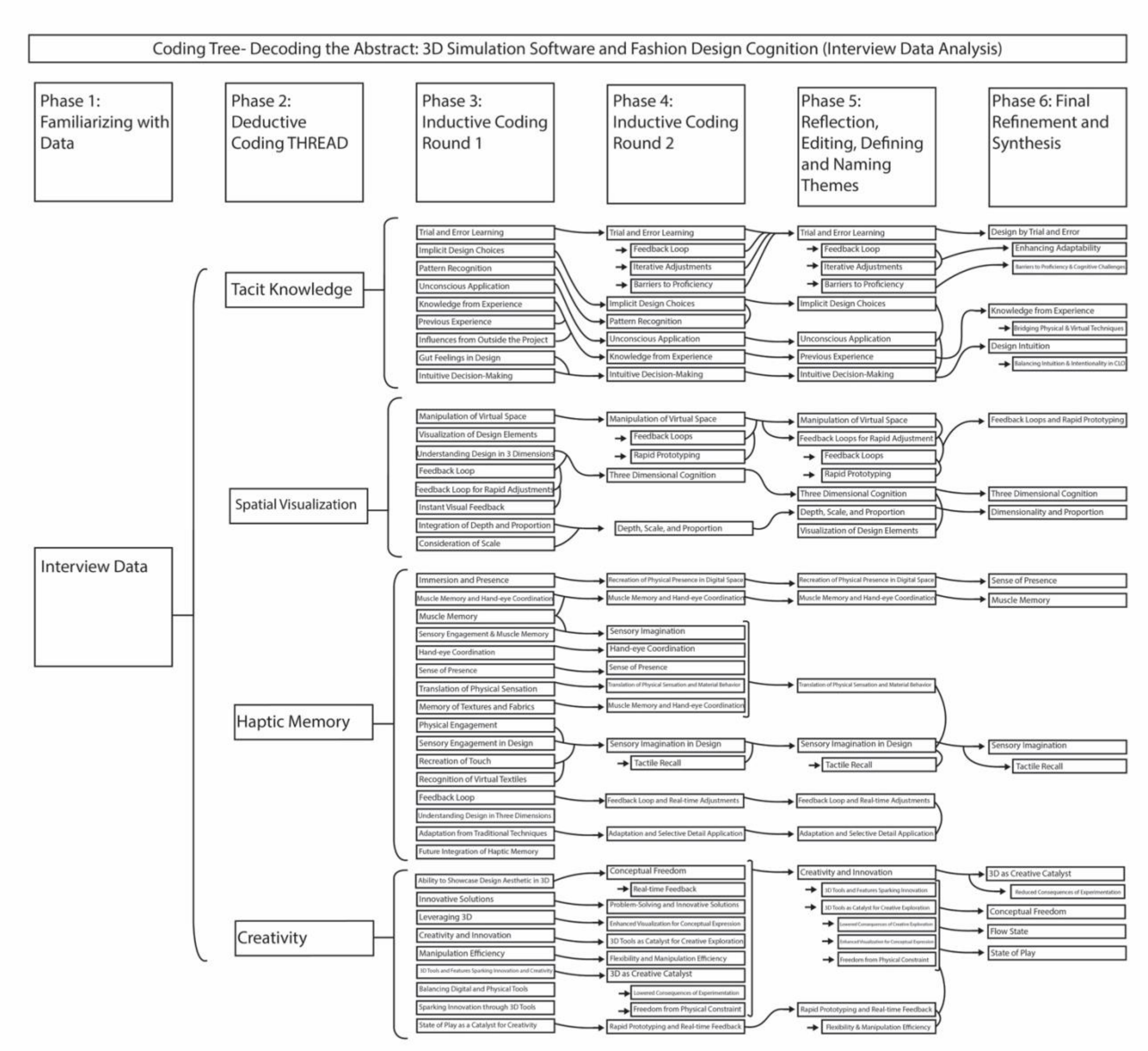


Figure 4.2

Coding Tree: Decoding the Abstract: 3D Simulation Software and Fashion Design Cognition

Trustworthiness

According to Chambliss and Schutt, the act of research and observation makes a certain unnatural environmental element unavoidable (2019). As students participated in a recorded interview, they naturally had a heightened awareness of their actions which may have had some effect on the results. The participants were thoroughly briefed that there are essentially no wrong choices or ways to learn and design and that the study objective is to glean an understanding of their cognitive processes.

In an effort to establish a rapport with interviewees, each interview session took on a casual, demonstrative format, with a bit of small talk before getting into the tenet-focused questions. Briggs (1986) states that small talk may also aid in determining the state of mind of the participant before delving into the interview. In line with the constructivist paradigm in which this qualitative study is situated, was the recognition that the participant's voice includes so much more than verbal sound waves, it also encompasses the social context and embedded meaning (Bird, 2005). In this qualitative study that utilized a naturalistic inquiry approach to elucidate and archive fashion design cognition within 3D simulation software, several principles were employed to ensure research quality. Specific to naturalistic inquiry, credibility, transferability, dependability, and confirmability were considered (Lincoln & Guba, 1985). While I served as the instructor for the courses from which participants were recruited, this role did not significantly impact my findings beyond providing access to the student participants. My position did not influence the interpretation of results, as the study focused on documenting their cognitive processes rather than assessing their skill levels or performance. Additionally, participants were encouraged to engage in their natural workflows without concern for evaluation, reinforcing the study's emphasis on authentic design cognition.

Credibility

In qualitative studies, researchers acknowledge that each participant brings their unique perspective and understanding of reality and this recognition of multiple truths underscores the importance of capturing diverse viewpoints and experiences in the study (Erlingsson &

Brusiewicz, 2013). By embracing the ontological assumption of multiple realities, this research aimed to explore the rich tapestry of subjective realities and interpretations that are present when thinking in the 3D space, ensuring that the findings reflect the complexity and nuances inherent in human experiences (Lincoln & Guba, 1985).

Transferability

Transferability, or the extent to which findings can be applied to other contexts or populations, was addressed through detailed descriptions of the research methodology, including participant selection criteria, interview procedures, and data analysis techniques (Erlingsson & Brusiewicz, 2013). Additionally, the study aimed for saturation, wherein data collection continued until no new insights or themes emerged, thereby increasing the likelihood that findings were relevant and transferable to similar contexts or populations.

Dependability

Dependability refers to the stability and consistency of the research findings over time (Erlingsson & Brusiewicz, 2013). In this study, dependability was ensured through careful documentation of the research process, including detailed records of data collection and analysis procedures. Another way to show consistent findings, and therefore, dependability, was through peer debriefing and investigator triangulation. This was achieved by involving multiple researchers in data analysis to confirm findings and interpretations, thereby enhancing the credibility of the study.

Confirmability

Confirmability is defined as, "a degree of neutrality or the extent to which the findings of a study are shaped by the respondents and not by researcher bias, motivation, or interest (Erlingsson & Brusiewicz, 2013, p.98). To enhance confirmability, the researcher employed reflexive journaling to reflect on their own biases and assumptions and how these may have influenced the research process. According to Cowan (1998), much of the trustworthiness in naturalistic inquiry is found in the utilization of reflexive journaling. By critically reflecting on their background and experiences, the researcher mitigated the influence of personal biases on the interpretation of findings, thereby enhancing the validity and credibility of the study.

Methodological Transparency

Methodological transparency was prioritized by clearly articulating the research design, data collection methods, and analysis techniques. Specifically, artifact interviews were utilized to elucidate and archive fashion design cognition. Participants were encouraged to visually represent their design processes through sketches and 3D renders, providing rich data that captured their cognitive thought processes and decision-making strategies. This transparent approach allowed for the documentation of participants' experiences in working with 3D simulation software, ensuring clarity in data collection and analysis procedures.

Through the application of these principles, this qualitative study aimed to ensure research quality and rigor in elucidating and archiving fashion design cognition within 3D simulation software. By adhering to methodological transparency, reflexivity, and member checking, the study sought to provide valuable insights into the cognitive processes involved in fashion design in the virtual environment, thereby contributing to the advancement of knowledge in the field.

Findings

The findings of this study provided a nuanced view of the cognitive processes shaping virtual fashion design, framed through the four tenets of the THREAD framework of fashion thinking related to design cognition: Tacit Knowledge, Spatial Visualization, Haptic Memory, and Creativity. Insights from student designer interviews revealed how virtual tools like CLO foster a dynamic interplay between foundational skills and digital experimentation. Tacit Knowledge emerged as a cornerstone, as designers relied on prior experience, instinctual decision-making, and iterative learning to navigate the digital design space. However, the ease of enacting changes in virtual environments sometimes detracted from adhering to a pre-conceptualized, cohesive design initiative. Spatial Visualization was cultivated as designers engaged with depth, proportion, and scale in a fluid, real-time 3D environment supported by rapid feedback and prototyping loops. Yet, this immediacy reduced opportunities for reflection, leading to rash decisions that were not always grounded in foundational skills. Haptic Memory, while requiring time to develop as a familiar skillset, played a crucial role in connecting sensory imagination and tactile recall. It bridged physical pattern-making experience with digital adjustments, fostering a tangible sense of presence within CLO's interface. Creativity also appeared to flourish in the virtual environment, empowering designers to experiment freely, push conceptual boundaries, and enter immersive "flow states" that drive innovation. Despite these strengths, the findings also highlighted significant challenges. Students with limited physical pattern-making experience often relied heavily on trial-and-error methods, which impeded their understanding of traditional techniques and also weakened the integration of foundational knowledge into virtual design workflows. These challenges underscored the need for balance in fashion design pedagogy. Digital exploration must be grounded in strong educational foundations in physical construction methods. This balance ensures that CLO enhances both technical proficiency and creative potential, rather than substituting one for the other. These findings not only archived the cognitive praxis of virtual fashion design but also elucidated the distinctive cognitive pathways activated in virtual environments and their potential implications.

Tacit Knowledge

In analyzing students' interactions with the 3D design software CLO, it was found that tacit knowledge played a significant role in guiding their design decisions. In the virtual environment, tacit knowledge manifested through knowledge from experience, design intuition, and trial and error methods. Tacit knowledge, a type of unspoken, experience-based understanding (Sternberg & Hedlund, 2002; Sternberg et al., 2000), allowed students to intuitively navigate CLO's interface and make rapid, flexible design choices. The software’s immediate 3D visual feedback encouraged a trial-and-error learning cycle, which fostered experimentation and facilitated quick adjustments compared to the slower, more manual processes of traditional garment construction. This ability to experiment freely and instantly reflected a shift in design methodology, where both digital proficiency and foundational physical garment construction experience were crucial to students’ creative processes.

Knowledge from Experience

This integration of the digital with physical know-how of construction highlighted how students applied knowledge from experience, demonstrating how their hands-on understanding of traditional techniques informed and facilitated their navigation of CLO’s virtual tools. This finding is demonstrated by one student’s comment: “Experience in person definitely translates to CLO. 100%,” pointing to how foundational in-person pattern-making skills creates a smoother transition to virtual tools. This tacit knowledge allowed them to adapt quicker, as they could pull from an existing knowledge base. Another student noted, “I’ve had a lot of experience trying to get things to fit right on people,” which informed her approach to digital adjustments. These insights, gained from hours spent in the studio, illustrated how students merged hands-on design knowledge with digital acumen. A student explained, “I think it would probably be pretty difficult to not know real life patterning first and move to CLO," underscoring how foundational physical experience is to virtual proficiency in fashion design, marking an essential part of tacit knowledge. Another student also echoed this notion, purporting that, "If you kind of know, like where curves are more necessary in patterns from doing flat pattern, it's easier to do it in CLO".

Experience-based intuition played a significant role in precise, real-time adjustments within the virtual space. One student shared, "If I do the armhole a bit bigger, I know how I have to change the sleeves pattern in order to make it fit," showcasing an understanding of the interdependencies in pattern-making adjustments, and added, "because I'm so used to working on bodices and sleeves in person, I know how to manipulate those elements." The student instinctively recognized that altering one pattern piece, such as the armscye, necessitated corresponding trueing of connected pieces. Students also adapted strategies from their real-world experiences to problem-solve in the virtual environment. One noted, "Sometimes it's like, oh, that didn't work. But most of the time I'm able to just kind of adjust it a little based on just my knowledge of how things work in the real world." This ability to translate real-world skills into digital solutions highlighted the seamless integration of practical knowledge into the 3D design process.

Students described actively integrating in-class techniques into CLO's digital environment. For example, one student shared, "Using, for instance, the accordion ball technique which I did in Tech Studio I with Dr. Sarah...I was able to take that experience from those classes and put it on to CLO." Another described how they "had to, like, reset and think of, like, how did I even do this in person? And how do I apply that and put it into the CLO world and work it from there?" Past familiarity with other software such as Illustrator unconsciously informed their approach: "I definitely am comfortable in Illustrator. So, like I use those [hotkeys] all the time... sometimes I'll just like look it up so that I remember the hotkey instead of trying to figure out where whatever tool is." While this prior knowledge streamlined the design process, it also revealed a challenge: the necessity to constantly recalibrate between workflows. Students noted occasional struggles to "re-familiarize" themselves with CLO after breaks, pointing to the reliance on unspoken, experience-driven knowledge that requires consistent practice to maintain.

Design Intuition

The interview findings underscored how repeated use of 3D simulation software cultivated an increasingly intuitive mastery, where design decisions were driven by an unconscious application of tacit skills honed through regular practice in both physical and virtual settings. This reflected a growing familiarity with the software, captured in one student's statement, which was echoed by other participants across data collection: "After a while, CLO became very intuitive… just as intuitive as…in person." Over time, digital pattern adjustments became second nature, marking a shift from conscious effort to an almost instinctual process. This transition reflected an implicit understanding of CLO's tools and interface, where designing in CLO had an increasingly similar intuitive feel to draping and pinning a garment in the real world.

This notion was echoed by another student, who explained, "having used it for, I don't know, maybe about a year now, it's come a lot easier." This illustrated how consistent practice leads to a natural ease with the software. Familiarity enabled students to effortlessly transfer their physical pattern-making knowledge into the virtual environment. This translation suggests that using a laptop, trackpad, and mouse becomes as instinctive for students as using their hands to manipulate a drape or flat pattern. Such automaticity, although it takes time to garner, ultimately supports a seamless design process. This instinctual proficiency comes with challenges, illustrated by one student's statement, "Since then, it's just about like, what do I think needs to happen, and not, what I know needs to happen because I'm still getting comfortable with it." This statement reflected a period of uncertainty where this intuitive problem-solving is not yet fully formed but is starting to emerge. Another participant described, "I can't even tell you how I managed to do the slit… but it ended up working," underscoring the reliance on tacit knowledge and instinct when explicit solutions are unavailable. These moments of uncertainty revealed the ongoing learning curve associated with mastering CLO's tools. The findings highlighted how students seemed to rely on instinctual adjustments in the virtual environment, informed by hands-on experience rather than strict adherence to rules. Instead of feeling the material with their hands, they relied on prior hands-on knowledge, instinct, and software output to guide their digital adjustments.

In addition, it's important to note the role that immediate software feedback played in intuitive cognition. The real-time feedback provided by the 3D simulation encouraged bold, spontaneous pattern-making choices. One student explained "I think that having the 3D window available…leads you to make kind of more bold pattern making choices." The student was referring to the 3D simulation tab, where the avatar and garment respond directly to commands in the 2D window. This workflow fostered creativity and a fluid flow of ideas because the student could see immediate visual feedback on their design and patternmaking choices and actions. This concept of "immediate gratification" surfaced as students experienced instant visualization of adjustments, which supported adaptive, intuitive decision-making.

While CLO's dynamic, iterative nature did foster creative exploration, it also led to over-reliance on intuition at the expense of mastering foundational design principles. The software's immediacy—allowing students to adjust points, simulate changes, and visualize garments in real time—offers a significant advantage in terms of efficiency and adaptability. However, this efficiency inadvertently discouraged students from engaging deeply with traditional patternmaking techniques or seeking guidance from textbooks and other foundational resources. For instance, students working in CLO resolved issues like drawing and sewing darts through instinct and repetitive experimentation rather than consulting technical references. One student reflected, “I just keep going, trying different methods,” underscoring a reliance on intuition to problem-solve. While this approach builds confidence and resilience, it risks bypassing the structured knowledge that comes from learning the “proper” methods of patternmaking. Over time, this could result in gaps in technical proficiency, as students may not develop a strong grasp of the theoretical underpinnings of garment construction. Also, the speed and ease of CLO’s workflow might encourage impulsive decision-making. Unlike traditional environments, where drafting, cutting, sewing, and reworking involve significant time and resources, CLO allows for almost instant corrections and adjustments. This can lead to a "just try things until it works" mentality, as one student described: “Sometimes I just pick whatever up and see how it goes from there.” While this spontaneity can spark creativity, it might also limit the deliberate and reflective decision-making process fostered by traditional methods.

Design by Trial and Error

This balance between spontaneity and intentionality often manifested in a trial-and-error approach, where students relied on the intuitive nature of CLO to experiment and iterate fluidly. Students described CLO as “more intuitive than Illustrator or Photoshop,” highlighting how this way of knowing enables them to navigate the software fluidly, in contrast to other 2D digital tools. This intuitive ease appeared to encourage instinctual design choices, where students used the software’s spatial tool layout to make rapid, flexible adjustments—a process they likened to “try something out and then go back and try a different thing.” Students described this trial-and-error learning cycle within CLO, wherein immediate 3D visual feedback on pattern adjustments can be seen articulated in the 3D window on the avatar just seconds after hitting the simulation button, fostering rapid experimentation. As one student noted, “you see the immediate impact of what you do… and immediately see what happens in 3D.” The tacit nature of the design process facilitated by CLO and other 3D simulation software programs for fashion design provides a low-risk environment for rapid experimentation and refinement. This trial-and-error approach mirrors traditional design practices but is greatly enhanced by CLO’s virtual capabilities. One student remarked, “It’s like the trial-and-error part where I just keep going, trying different methods,” illustrating how setbacks were seen as opportunities to adapt and recalibrate.

The immediacy of CLO’s feedback loop allowed students to make real-time adjustments, fostering a fluid and intuitive approach to design. As one participant explained, “You can kind of try something out, in the 2D or 3D window and then see what the impact of that change you made is,” emphasizing the platform’s ability to streamline the revision process. Another highlighted the efficiency of virtual tools: “You don’t have to sit there and re-draft and re-sew your mock-up… you can always just go back and edit something small and then try to re-sew it in CLO.” These features enabled students to iterate quickly, building tacit knowledge through constant experimentation.

CLO’s ability to integrate 2D pattern manipulation with 3D garment visualization is a standout feature that simplifies traditionally labor-intensive tasks and maps to students’ previous experience working with flat patterns. One student described how the platform enables precision adjustments: “Instead of having to… I could draw the general shape and then position it where I want in the 3D window.” This seamless transition allowed students to explore ideas and refine patterns in ways that would be more cumbersome if flat-patterning. As another participant observed, “In CLO, it’s so much easier to just adjust a point and see how it’s going to fit.” One student observed, “the trial and error of it is a lot quicker in 3D than it is in physical work.” This real-time feedback reinforced design instincts. For instance, when one student struggled to add pleats to a garment, she noted, “It took me a really long time to try and understand and figure out how to put pleats in, because it’s so complicated.” She described that through persistent trial and error, she gradually learned how to manipulate the virtual tools to achieve the desired effect, a process that reflects the tacit, trial and error cognition that CLO supports.

The 3D simulation software environment supports creative adaptability. Students noted how resolving initial challenges builds confidence to tackle more complex designs. For instance, one student said, “So once that got figured out I was like, okay, I think I can go ahead and try to do the slit again.” This ability to experiment freely encouraged resilience and innovation, as students explored new ideas in real time. The platform’s 3D visualization and virtual textures often sparked creative pivots, such as shifting from silk to velvet mid-project, as discussed by one student. However, the trial-and-error workflow was not without frustrations. While real-time feedback encouraged bold experimentation, troubleshooting errors were challenging, requiring an adaptable mindset. One participant explained, “I will click simulate to see what's happening and... be like, okay, that's still just messed up. I gotta go back and forth.” Another added, “If it’s not working then I’ll get confused... trying to figure out what I need to fix.”

CLO’s technical demands posed barriers to students’ proficiency. One participant noted, “You know what you want to do, you’re just not quite sure how to get there in CLO and what tools to use,” underscoring the cognitive challenges of navigating an unfamiliar interface that lends itself to tacit thinking. This lack of familiarity hindered the seamless execution of creative visions, as another student reflected while troubleshooting the sewing of a skirt: “I feel like if I was really proficient in it, then I would know exactly what’s wrong.” These struggles often led to reliance on intuition and persistence to overcome obstacles. For instance, when designing a specialty asymmetrical bodice, one student explained that their process, “was more of like a feeling,” demonstrating how instinct plays a crucial role in uncertain contexts. Technical skill gaps also limited students’ ability to fully leverage the platform’s potential, as illustrated by one participant’s frustration: “Sometimes if I just can’t figure it out... it’s not helpful.”

Spatial Visualization

In examining visualization within the THREAD framework, the findings revealed how 3D simulation software engages students spatially, promoting unique cognitive processes and presenting challenges. As students worked in the virtual environment, they relied on spatial visualization skills to navigate and manipulate virtual space, enabling them to conceptualize and construct designs that bridge 2D patterns and 3D garments. The findings highlighted key aspects of spatial visualization—including three-dimensional cognition, dimensionality, and proportion—which together supported students' ability to prototype, adjust, and refine designs in the virtual environment. This process was reinforced by feedback loops and rapid prototyping capabilities, which fostered iterative learning and strengthened students’ capacity to visualize and execute complex designs.

Three-Dimensional Cognition

3D simulation software’s immediate visual feedback enabled students to dynamically assess spatial relationships and refine designs in real time. As one student noted, “It’s really hard to visualize patterns sometimes in person,” emphasizing that CLO provides a multidimensional perspective that aids spatial comprehension. Another student described this effect as “Seeing the instant changes in how [your] design looks on the screen… helps you kind of envision your design come to life," underscoring how the software's immediate feedback builds spatial cognition. This capability bridges the gap between virtual and physical design, allowing students to assess aspects like fit, movement, and form as if working with tangible made objects.

The ability to see designs "in front of your face" was described as helpful, reflecting how CLO's interface supports their cognitive understanding of spatial relationships. For instance, the preference for working directly in the 3D window by drawing with the 3D pen within CLO rather than patterning in the 2D window demonstrated a reliance on spatial visualization. One participant explained, "I feel like I'm definitely more successful when I do the drape-type situation on the 3D side than me trying to do... a flat pattern on the 2D side." This approach enabled them to visualize while they work, dynamically assessing fit and seeing the results on the screen. The utility of the 3D pen tool further illustrated this point. Students used it to draw style lines directly on the avatar, which enhanced their ability to understand the role of proportion in garment fitting. One participant shared, "I think it's easier because it allows the fit to end up being correct on the avatar in the end," underscoring how CLO's virtual environment supports spatial understanding. Another echoed this sentiment, explaining, "You can try something out, in the 2D or 3D window and then immediately see what the impact of that change is." CLO's real-time feedback mechanisms not only accelerated design iteration but also enhanced students' ability to conceptualize garments in a spatially rich and interactive way.

Dimensionality and Proportion

This interactive feedback loop fostered a deeper understanding of spatial relationships, allowing students to engage more critically with dimensionality and proportion. The ability to adjust proportions in CLO gave students the freedom to explore design elements with precision that went beyond the constraints of physical materials. For example, one student described how designing a hood is more efficient in CLO: "With the hood… I could draw the general shape and then position it where I want in the 3D window." Hoods can be challenging to fit properly due to the complex curves of the head and neck, often requiring curved seams, darts, or multiple panels to achieve the right contours without gaping or being too tight. Additionally, hoods must connect seamlessly to the garment's neckline, demanding careful attention to drafting the attachment points, including the shape and size of the neckline opening, shoulder slope, and front bodice.

Another student mentioned how "engaging with proportions would be in your head if you're patternmaking physically... [CLO] expedited the process," when discussing how CLO streamlines scaling and grading. 3D simulation software expedites the process through automated tools that allow designers to apply consistent size adjustments quickly, while also providing real-time 3D visualization to see how changes impact fit on various avatars. Customizable size sets, intuitive pattern adjustment features, and efficient layering helped ensure accuracy and maintain proportions across different sizes, significantly reducing the time spent on manual adjustments. In addition, CLO allowed students to build a dual awareness of virtual and physical scales, aiding their ability to translate digital designs into real-world measurements. For example, a student who often uses plotters in conjunction with virtual patterns remarked, "I put in a one-by-one square and I'm like, okay, when you print this, this square has to be one inch by one inch," underscoring a precise understanding of spatial alignment between digital and physical formats, ensuring that when the patterns are printed out, they can be constructed at the correct scale.

A senior capstone student highlighted the importance of scale when working with different models, stating, "My dress form is a different body shape compared to my avatar or the real model," when discussing how garment proportions must adapt between virtual avatars and real bodies. This awareness was crucial when manipulating virtual space in CLO, as even minor adjustments can significantly impact other design elements. A student illustrated this complexity by noting, "You start like changing one line, and then it kind of like does a funky job on the other part," showcasing the skill required to manage these interconnected changes in 3D design.

Feedback Loops and Rapid Prototyping

This intricate interplay of adjustments highlights the importance of feedback loops and rapid prototyping, as CLO's real-time simulation enabled students to quickly visualize. CLO's immediate simulation and interactive render features provided a feedback loop that accelerates the design process by allowing students to see the effects of tweaks instantly, revolutionizing rapid prototyping. Rapid prototyping is "a group of techniques used to quickly fabricate a scale model or a part" (Schlick, 2024). One student explained, "In CLO, you make one little tweak and then re-simulate. You can see it immediately." This rapid feedback loop let students experiment and learn from mistakes, which was crucial in building confidence and spatial intelligence in the virtual environment. Instead of spending hours reworking a physical prototype, students observed and corrected any fitting or design issues within seconds.

Students frequently emphasized the value of CLO's feedback mechanisms in their design process and the value of being able to prototype their designs in CLO before translating to physical patterns. One participant shared, "I was able to see how my mockup or like, my pattern was… so being able to edit it on CLO and seeing the result, I tried it on the muslin." Another student described their experience, highlighting that building the patterns in CLO first resulted in a "perfect" physical execution: "I think about two of the outfits that I made. I was able to see how my mockup or like, my pattern was… and it was perfect." CLO's facilitation of rapid prototyping enabled students to adjust and finalize patterns in a time-efficient and resource-conscious manner. Another remarked, “I made five [physical] samples, and none of them worked... it’s just such a waste of fabric… and I realized in CLO that it really helps things go faster.” Yet another student echoed this message, “Like the fashion show that I was in, because at least I was able to try out my pattern pieces on CLO without having to physically make them.” By minimizing resource-heavy trial and error in the physical environment, students acknowledged that 3D simulation software enables iterative learning and supports sustainable design practices.

Haptic Memory

Haptic memory is a key tenet within the THREAD framework, capturing the sensory and embodied experiences of designers as they navigate the virtual workspace. The term “haptics” refers to the sense of touch that enables us to perceive the boundaries of our physical being by recognizing where the body begins and where it ends (Kern et al., 2023). Haptic memory, in this context, refered to the mental simulation of touch, texture, and physical interaction that are typically associated with tangible materials but are instead accessed through digital tools. The findings in this area were organized into three primary categories—sensory imagination, muscle memory, and a sense of physical presence—each highlighting how designers engage tactile recall, internalize material handling, and maintain a physical connection to their work, even in the absence of a physical garment.

Sensory Imagination

Among these, sensory imagination emerged as a key strategy, enabling students to mentally simulate the tactile qualities of fabrics and materials, bridging the gap left by the absence of physical touch in CLO. One student’s comment, “I love the hand tool... because you can pull it and kind of see like how it's going to move when it snaps back, like where it lands," reflected this sensory engagement. The virtual tool allowed students to simulate real fabric behavior mentally, blending their understanding of material properties with the digital manipulation capabilities. Additionally, students replicated physical gestures in CLO, such as using the pin tool to virtually "pin" the garment, which a student designer described as "just moving it like I would physically, you know, pin something on somebody." This virtual mimicry of physical tasks underscored their reliance on haptic memory and sensory imagination, where they mentally recreated the feel and behavior of fabric as if working hands-on.

The students' interview transcripts revealed a deep-rooted understanding of fabric behavior, drawn from physical experience. They mentioned setting stretch and reflection properties, visualizing how fabric might lay, and relying on memory to inform these adjustments. One student shared, "you can change the stretch, you can change how it lays," when illustrating how prior experience with real materials guided them in defining virtual attributes that lack physical validation. Even the choice of where to place trims or fastenings like zippers and buttons was guided by physical familiarity: "I can actually change the points of where things are in 3D, and I can adjust it and make it fit a certain part of the body really nice and quick." While CLO lacks tactile feedback, students noted that it still offers a level of sensory engagement, when they mentioned different tools, and described imagining the physical behavior of fabric in a virtual space. This fluid adjustment process showedde how virtual design skills blend with a tactile understanding, enabling students to make decisions grounded in physical intuition.

Muscle Memory

As students gained more experience with CLO, their physical skills from traditional design processes evolve into new muscle memory specific to virtual tools. One student discussed this adaptation, saying, "There's a whole new set of muscle memory that you have to develop when learning the program." This shift in muscle memory emphasized the cognitive process of translating physical skills into the virtual design space, where students often toggled between functions and tools with hot keys, with increasing fluidity. Another student humorously noted that they even catch themselves using CLO-specific shortcuts in other software, indicating how their hand-eye coordination and tool familiarity are becoming ingrained.

Additionally, students described parallels between digital and physical manipulation of fabrics. One noted, "I look at [the virtual fabrics] more as, texture, I guess…In terms of moving [the fabric] and trying to like, get gathers... I think there's a similarity in there." The similarity the student was referring to describes how the hand tool in CLO mimics the tactile experience of handling physical fabric. Another student commented, "whether you're using a mouse or trackpad, there's kind of like a hand-eye coordination thing going on," further underscoring the physicality of virtual design. One even wished for greater tactile interaction, remarking, "Playing with the fabric, it would be nice to have two hands in CLO," suggesting a desire for enhanced simulation features that could deepen the connection between physical and digital methods. This adaptation shows that while the actions were virtual, the physical engagement with digital design tools mirrored traditional design processes, making these skills increasingly intuitive.

Sense of Presence

This seamless integration of physicality into virtual actions underscored a sense of presence, as students reported feeling deeply immersed in the virtual design process, almost as if interacting with tangible materials. One student captured this experience, saying, "Once you get over the learning curve... it feels like you're present with the garment and fabric in some way." This presence suggested that digital design becomes a familiar space over time, allowing students to mentally transport their skills into a virtual environment where they feel “with” the garment, even without physical interaction. This immersion was strengthened by adaptations from traditional techniques, such as pattern making, that some students found easier to apply digitally. For instance, one student noted, “It works so much better than trying to build a pattern from scratch... sit on the floor and get out your pencils and paper.” This transition from physical to digital design enhanced their cognitive agility, allowing them to apply their haptic memory more efficiently, making adjustments digitally before moving to physical production.

A student described the immersive nature of CLO, sharing, "...it’s kind of like I get lost in the digital world... I was just, you know, seeing what lace style looked good on the avatar." Another echoed this sentiment, saying, "...I was in the avatar’s life and making outfits and all that." This sense of being “lost in the digital world” mirrored traditional hands-on design immersion, demonstrating how virtual environments can replicate and even enhance creative engagement. By fostering this deep level of focus and interaction, CLO enabled students to explore and iterate in ways that felt as tangible and engaging as working in a physical studio.

Creativity

Creativity, a tenet of the THREAD framework’s duality of design cognition, in virtual design, was characterized by an interplay between technological affordances and cognitive freedom, where the digital workspace becomes a creative catalyst. The findings were categorized into three main areas—3D as a creative catalyst, conceptual freedom, fluidity of flow, and the state of play—which together showcased how virtual tools lower the perceived risks of experimentation, eliminate physical constraints, and support an immersive flow state, all of which amplify the designer's creative latitude.

3D as Creative Catalyst

The features of CLO 3D—such as fabric customization, avatar manipulation, and instant adjustments—were found to enhance students' creative abilities. One student stated, “I like to change the different colors and textures of the fabric that I'm using,” which shows how CLO’s digital fabric library and customizations sparked visual creativity. This ability to experiment with color, texture, and material properties in real time supports a wider range of creative expressions than would typically be feasible in a physical environment, a sentiment echoed by many of the participants. One student described using CLO to quickly prototype, making it easier to visualize and iterate on ideas, saying, “If I adjust this, I know that it’s going to change the shape in 3D... I think it makes it a little easier to see it right away.” This instant visualization feature helped students push their ideas forward by reducing the time and labor needed for creative experimentation. One participant elaborated, "[You can] immediately see what the impact of that change you made is." The ability to iterate quickly using CLO’s features supported creativity. The participant noted how CLO simplifies the process of revision: “It’s easier to go back and edit something small and then try to re-sew it.” This ease of experimentation fostered innovation and enhanced the designer’s creative output.

The instant feedback loop provided by 3D simulation software allowed students to test and adjust designs in real time, significantly enhancing their creative workflows. The immediacy with which changes were visualized encouraged experimentation and aligned with the sentiments of many students, who valued the ability to make rapid adjustments and gain immediate insight into how design changes will look and behave. This capability supported a more iterative and dynamic creative process, enabling students to experiment, critique, and refine their work in a matter of minutes. One student noted, “The consequences for experimentation are a lot lower in

CLO," which emboldened students to test unconventional pattern-making methods and material choices. This freedom encouraged risk-taking and innovative thinking, as students felt more confident to try bold ideas without the fear of wasting resources. For example, they can "play around with materials in a really extravagant way," exploring new textures and finishes that might be too costly or impractical in traditional design workflows.

However, this lowered barrier to experimentation sometimes also led to unintended consequences in the design process. The ease of making changes in the 3D environment reduced adherence to the original plan or a thoughtfully developed design concept. One student reflected on their process: "I remember for one of the outfits that I did, I just wanted, like, a silky sheen. But then when I was on CLO, I saw that there was a velvet. And I loved the effect of that, so I changed the whole outfit look to include the velvet instead." While this adaptability fostered creative exploration, it also resulted in impulsive decision-making, potentially diverging from the initial design vision.

The virtual environment's flexibility and the reduced consequences of "just trying something" also encouraged a more spontaneous approach to problem-solving. As one student put it, "It's just about, what do I think needs to happen." While this intuitive mindset at times ignited creativity, it also sidelined established pattern-making principles and methods, which are critical for a deeper understanding of garment construction. At the same time, the software's agility in manipulating designs—such as quickly moving, resizing, and reshaping elements—enhanced the iterative process and supported ongoing refinement. The ability to "move things around in the 3D window quickly," as one student described, exemplifies how CLO 3D streamlines the design process by enabling rapid adjustments that would be far more cumbersome in traditional physical prototyping. This adaptability allowed students to efficiently refine fit, structure, and other critical design elements. However, while this efficiency supported a fast-paced, iterative workflow, it also led to a more superficial approach to problem-solving. The reduced time and necessity for reflection inherent in this process appeared to sometimes limit students' opportunities to deeply engage with the challenges of garment construction.

For example, one student emphasized the advantage of CLO's tools for tackling complex garments, such as bustiers, noting, "That's a huge bonus when working on CLO instead of working in person." Another elaborated, "So, yes, a huge one would be like with bustier. I would probably not have been able to do that like well of a work in person." While these tools make intricate designs more accessible, they also risk diluting the learning experience by automating many of the manual skills required in physical garment construction. Creating a boned bustier in a traditional setting requires mastering intricate techniques, such as draping, inserting boning, creating casings, and applying fusings or interfacing—all of which involve specific stitch methods and a high degree of precision and manual dexterity. In 3D simulation software, many of these steps are simplified or bypassed. For instance, fabric presets simulate the structural effects of boning, but the boning itself is often added as internal lines, which prioritize visual accuracy over structural integrity. Similarly, seam allowances can be automatically generated and placed by the software, removing the need for students to develop the fine motor skills and spatial understanding required in tailoring. By automating these technical elements, 3D simulation software reduces barriers to experimentation and innovation, but it also risks fostering a surface-level understanding of garment construction. While the tools empowered students to create visually compelling designs, they may have inadvertently hindered the development of essential technical competencies, leaving gaps in foundational skills that are critical for success in physical design environments.

Conceptual Freedom

This trade-off is seemingly balanced by the conceptual freedom that 3D simulation software provides, allowing students to explore and realize abstract ideas with unprecedented ease. One student appreciated how CLO helps them translate ideas from imagination to the screen, saying, “I really like using [for], like, conceptual things... to take it out of my head and actually put it somewhere.” This digital representation is especially helpful for sharing designs with others during critiques or presentations, as it allows others to quickly grasp the vision without needing a completed physical prototype. Another student reflected on CLO’s role in showcasing their ideas during critiques, noting, “It makes it so much quicker for them to see... like, this is the way it’s going to look... without actually seeing it on the body.” This ability to showcase aesthetic choices and receive feedback early in the design process is essential for refining creative ideas and aligning them with others’ expectations.

CLO also acts as a platform for self-expression, enabling students to bring their aesthetic visions to life in a digital format. One participant shared, “I feel like [CLO] empowers me to express my creativity... I like to, show people, when I'm working. I kind of feel like, I guess just empowered by it because I feel like, a lot of people say that it's hard to navigate. So being able to be like, oh, like, wow, I'm able to do this. Like, I’m happy that I can at least show it off.” This empowerment fostered confidence and pride in their ability to master a challenging tool and use it to communicate their unique vision. Another student highlighted their independent use of CLO for creative projects, stating, “because I was kind of just like, I wanted to do this. Even in, for the fashion show, I wasn’t even told to do any 3D renderings, but I decided to anyways because I wanted to.” This underscores how CLO supports self-driven exploration and enhances students’ internal drive to push creative boundaries, even beyond formal assignments.

Flow State

This sense of creative freedom enabled some students to enter a fluid "flow" state in their design process, as described by one student: "CLO works so much better than trying to build a pattern from scratch… sit on the floor and get out your pencils and paper." She emphasized how the ease of working digitally allows her to get into a groove more quickly and effortlessly in a virtual format. This sense of flow is further enhanced by the software's instant feedback, which lets students visualize design elements immediately. One student remarked, "Seeing the instant changes… helps envision your design come to life." This ability to "see" how garments fit on avatars supported more accurate adjustments, allowing students to refine their work based on intuition and their "feel" for design, as another student noted: "The human eye… we can precisely say like, oh, this is wrong… we can just feel that it's off or something is off."

However, entering and maintaining this flow state was often contingent on the student's familiarity and comfort with the software. Students who had mastered the tools and interface described CLO as an exciting and immersive design tool that empowered their creative vision. For example, one student reflected, "it's just about like, what do I think needs to happen, and not what I know needs to happen because I'm still getting comfortable with it." This comment highlights how a lack of expertise in the software can lead to a more experimental but less structured approach, potentially hindering the ability to fully leverage its capabilities. Another student echoed this sentiment, expressing that, "You know what you want to do, you're just not quite sure how to get there in CLO and what tools to use," illustrating how limited familiarity can disrupt the creative flow. Some students even expressed that they find a better flow in physical design processes. One commented, "I have a better flow in real life," while another noted, "Doing it on a form in real life is more helpful for my design vision than doing it on

CLO." These remarks suggest that creative potential sometimes felt constrained by a lack of comfort with the virtual environment, where some students favored the tactile, immediate nature of physical design over digital tools.

Even for those who achieved a flow state in CLO, the streamlined process of working in the software sometimes led to skipped steps, with students opting to address them later during physical prototyping. One student explained, "In the virtual world… putting buttons in there for me doesn't really matter as much as the style and the shape and the fit. Because then if I decide that I'm going to print that out and build it, I can just put those in there myself." This highlighted how the digital environment encourages a focus on broader stylistic elements, while some finer details are deferred to physical construction. While CLO 3D facilitates a dynamic and immersive design experience for those who are adept with its tools, its effectiveness depends heavily on the user's level of familiarity. For some, the software enabled fluid creativity and experimentation, but for others, the virtual environment posed a barrier to achieving their full design potential.

State of Play

Viewing 3D simulation software like CLO through the lens of play served as a powerful catalyst for creativity. One student likened the experience to gaming in childhood, highlighting how creativity is driven by curiosity and playful experimentation. Just as children engage in video games with a sense of exploration, the student designers who approached 3D simulation software with a similar mindset—viewing it not just as a tool, but as a space for imaginative discovery- expressed getting the most utility out of it. One student noted when reflecting on a game played in their teenage years, "...I was in the character's life and making outfits and all that." The digital space became a sandbox for creative exploration, where students who were able to generate a certain comfortability with the interface approached design challenges as opportunities for discovery rather than obstacles to overcome.

For some students, viewing CLO as a game-like environment nurtured a state of play and helped them overcome the big learning curve. They shared, “Yeah, I try to make it fun. I guess I also come up with that as, like a video game. Yeah. And I love playing video games. I think looking at it that way helped me.” This mindset helped students move past the initial frustration that comes with a lack of familiarity with software tools and interface and the steep learning curve presented by 3D simulation software. Interviews revealed that if students viewed the software solely as a technical tool rather than an interactive and enjoyable platform, they found it harder to connect emotionally and immerse themselves in the process. For example, another student further reflected on how this playful mindset influences their design process: "I remember like some of the other students would ask me, like, do you get this?... I was able to take that enjoyment and think about it in the fun space rather than thinking of it in a technical way."

The metaphor of CLO as a "game expansion pack" also highlighted how this playful approach fostered intrinsic motivation. As one student compared CLO to the game of their childhood, “[CLO] is kind of like an expansion pack [of a video game], because before you had the outfits and they all came in gray and you just had to put whatever color you wanted and whatever shade or pattern. And with CLO, it was like, oh my gosh, I'm doing this. But like now I'm actually creating everything from scratch. So it was really exciting for me, honestly, going into this.” This comparison underscored the student’s mindset of play, which set them up to view problems encountered with empowerment and excitement, turning the design process into an engaging, dynamic experience.

Discussion

This study aimed to analyze, document, and clarify the cognitive processes inherent in 3D virtual fashion design, employing the THREAD framework to conceptualize fashion design as cognitive praxis. Additionally, it assessed the THREAD model's effectiveness as a theoretical framework for understanding these cognitive processes in the context of 3D virtual design. The findings demonstrated that the THREAD model effectively captures and organizes key aspects of design cognition, offering valuable insights into creativity, tacit knowledge, visualization, and haptic memory within a virtual environment. By applying the THREAD framework, this research not only validated its viability but also highlighted its potential as a pedagogical tool and analytical model for advancing fashion design education. The THREAD framework successfully provided a structured approach for analyzing the cognitive dimensions of 3D fashion design. Its emphasis on interconnectedness and continuity aligns with the iterative and holistic nature of fashion thinking. By isolating and examining the four tenets relevant to design cognition—creativity, tacit knowledge, visualization, and haptic memory—the framework facilitated a comprehensive analysis of the mental processes that designers engage with when using CLO 3D software.

Specifically, the study revealed how designers leverage creativity to generate novel ideas, using CLO’s digital tools to explore possibilities beyond physical limitations. The emphasis on tacit knowledge underscored the role of prior experiences and intuitive decision-making, which were evident as participants adapted to the software's constraints and capabilities. Visualization proved integral to bridging abstract concepts and tangible outcomes, with participants effectively using the software’s simulation tools to refine their designs. Lastly, the inclusion of haptic memory highlighted the sensory engagement of designers as they translated tactile experiences into virtual manipulations, underscoring the embodied nature of fashion cognition even in a digital context. The THREAD framework's utility extends beyond theoretical analysis to practical applications in education and practice. Its systematic categorization of cognitive processes enables educators to scaffold learning experiences in virtual fashion design. For example, teaching strategies can be developed to explicitly target each tenet, such as fostering creativity through ideation and conceptualization exercises, enhancing tacit knowledge via iterative practice, training visualization skills through 3D modeling rapid prototyping, and encouraging haptic memory by drawing parallels between physical and virtual manipulations.

The framework also proved effective in organizing and interpreting qualitative data. By categorizing insights from interviews and observations according to the THREAD tenets, the model ensured a comprehensive understanding of participants' cognitive processes. The application of the THREAD model in this study underscores its relevance in the context of advancing fashion design pedagogy. Virtual tools like CLO challenge traditional modes of teaching by requiring students to integrate digital skills with foundational design cognition. THREAD provides a lens through which educators can evaluate and adapt their approaches, ensuring that students develop the cognitive flexibility needed for both virtual and physical design contexts. Specific to each tenet, the research findings illuminate how 3D simulation software, specifically CLO, manifests creativity, tacit knowledge, visualization, and haptic memory within the virtual environment.

Tacit Knowledge

This study highlighted the transformative role of 3D simulation software, such as CLO, in fostering tacit knowledge—a form of practical intelligence derived from experience and context-specific learning (Sternberg & Hedlund, 2002; Sternberg et al., 2000). Tacit knowledge, which has been described as, “an intelligence expressing itself in other means than words” (Anni Albers,1944, p. 27), manifested through students' intuitive responses to CLO’s interface, shaping their design processes in ways they were not able to explicitly recognize or articulate. CLO enabled students to engage intuitively with design tasks through iterative workflows and real-time feedback, bridging mental and physical processes and synchronizing design thinking with technical execution (Siu & Dilnot, 2001). However, the findings revealed a duality: while the software enhanced intuitive problem-solving, its efficacy depended heavily on students' foundational knowledge in physical patternmaking and garment construction. Students with strong foundational skills found CLO "very intuitive… just as intuitive as…in person," suggesting that tacit knowledge in virtual design emerges from prior hands-on experience. Conversely, students without such expertise relied on trial-and-error approaches, as one student noted, “I just keep going, trying different methods,” reflecting a reliance on instinct rather than technical principles. This perspective aligns with findings by Søberg and Chaudhuri (2017), who noted that trial and error in technical industries generates new learnings while saving time and reducing risks.

This intuitive experimentation, while fostering confidence and resilience, risks undermining the theoretical understanding essential for garment construction. Over time, the speed and ease of CLO’s workflow may encourage impulsive decision-making, exemplified by another student’s comment: “Sometimes I just pick whatever up and see how it goes from there.” However, these findings do align with Schön’s (1983) concept of reflective practice, where expertise evolves through iterative engagement. This phenomenon is further compounded by CLO’s ability to "front-load" the design process by enabling rapid prototyping and instant corrections (Thomke & Fujimoto, 2000). In this way, the software minimizes the divergent phase of design, where multiple solutions are explored. While this accelerates development, it risks eroding design discipline and increasing costs later in the process by allowing easy adjustments too late in the prototyping cycle (Fixson & Marion, 2012).

Tacit knowledge remains central to successful design education and industry practice, as it integrates intuition with structured expertise (Nonaka & Takeuchi, 1995). In engineering design, 3D CAD tools have shown similar effects, improving students' understanding of design challenges and knowledge-building (Taleyarkhan et al., 2018). However, these tools predominantly support convergent thinking, emphasizing technical problem-solving over the exploratory, divergent processes foundational to design cognition (Fixson & Marion, 2012). In fashion, maintaining a balance between these cognitive approaches is critical to cultivating both creativity and technical proficiency. Siu and Dilnot (2001) underscore the unique ability of 3D computer technology to re-contextualize craftsmanship within a digital "making environment." In CLO, design and making were often found to occur simultaneously, enabling students to merge their mental and physical processes with craft knowledge. However, to fully leverage this potential, educators must ensure that foundational skills in physical patternmaking and garment construction are integrated into virtual design curricula.

Spatial Visualization

One of the great affordances of 3D simulation software, such as CLO, is that it facilitates the engagement of spatial cognition and visualization skills. CLO's interface bridges the gap between the technical foundation and tangible outcomes by allowing designers to toggle between flat patterns (2D) and virtual garments (3D) in real-time. This iterative process supports Thomke and Fujimoto's (1989) idea that the visualization provided by computer simulation allows for faster problem-solving cycles, likely serving as a critical link between ideation and realization in design. Students manipulate virtual fabrics, textures, and colors, enabling them to assess the functional, expressive, and aesthetic aspects of their designs through visuals (Power, 2013; Ferwerda, 2003). The cognitive benefits of 3D design software's visualization capabilities can be explained through the Geon Theory proposed by Biederman (1985). According to this theory, spatial cognition is improved by mentally grouping primitive 3D shapes like cubes, cones, and cylinders, which form the building blocks of more complex structures. CLO capitalizes on this by providing students with an intuitive, visually immersive environment to manipulate design elements. Such virtual environments leverage human perceptual systems to enhance spatial understanding (Wann & Mon-Williams, 1996).

Research demonstrates that engaging with 3D virtual environments improves spatial knowledge representation, motivation, and contextual understanding (Dalgarno & Lee, 2010). In CLO, this manifested through the ability to analyze on-body garment relationships and interactions with avatars, fostering a deeper comprehension of proportion, fit, and movement (Park et al., 2010; Hwang & Hahn, 2017). One student reflected, "I can see how the garment moves and fits instantly," highlighting how CLO facilitates immediate and actionable insights into design feasibility. The use of 3D simulation in design education also mirrors broader learning value of spatial visualization skills across disciplines like architecture, engineering, and mathematics, gleaned by 3D software (Chen, 2004; Lowrie et al., 2019). Spatial visualization, defined as the ability to mentally manipulate objects in three dimensions in relation to space (McGee, 1979; Salthouse et al., 1990), is intrinsic to design thinking. It allows designers to assess spatial relationships, explore multiple perspectives, and iteratively refine their ideas.

Simulation software also aligns with Horwitz and Barowy’s (1994) assertion that visual experimentation enables students to engage with phenomena otherwise inaccessible, enabling students to experiment iteratively with virtual prototypes.

Haptic Memory

3D simulation software provides a unique platform for design that engages and cultivates haptic memory by blending sensory imagination with prior tactile experiences. The term "haptics" refers to the sensory perception of touch that defines the boundaries of physical being (Kern et al., 2023), and in the 3D fashion design environment, haptic memory was found to manifest as a mental simulation of touch, texture, and physical interaction. CLO enabled students to cultivate a certain virtual muscle memory, which could be described as a form of embodied knowledge fostered through sensory imagination and digital manipulation. These gamified and immersive properties of the interface encouraged sensory imagination, allowing students to simulate fabric behavior through tools like the hand and pin functions. The participant observation that "you can pull it and kind of see like how it's going to move when it snaps back" illustrates how the software mimics tactile recall and fabric behavior. Similarly, another student’s use of the pin tool—"just moving it like I would physically, you know, pin something on somebody"—underscores how CLO enables student designers to mentally recreate the physical feel and behavior of fabric, blending their understanding of material properties with digital interaction.

This blending of sensory imagination and tactile recall aligns with Nimkulrat’s (2012) concept of material thinking, described as "thinking through the hand manipulating a material" (p. 64). In this context, the act of creation is inseparable from sensory experience. Carter (2005) further emphasizes that materials serve as active participants in artistic intelligence, connecting the mind with the hands and eyes. 3D software mirrors this dynamic by enabling real-time experimentation with textures, draping, and fit, effectively simulating the physicality of crafting within a virtual environment. The hand tool, for instance, mimics the tactile experience of handling physical fabric, allowing students to engage their haptic memory intuitively.

As students adapt to the 3D environment, they described developing new forms of muscle memory specific to virtual tools. The intuitive engagement with tools like hotkeys reflects a cognitive shift to automation. One student humorously noted using CLO-specific shortcuts in other software, highlighting how the virtual environment becomes second nature. The realism offered by CLO's material simulations amplifies sensory engagement and presence, likely contributing to this sense of automation. This aligns with findings by Nebel et al. (2020) that realistic digital environments enhance emotional responses and cognitive engagement, leading to better learning outcomes. Lin et al. (2017) similarly observed that detailed imagery improves attention and memory stimulation. This realism fosters immersion, enabling students to interact with virtual textures and garments as though they were physical. The sense of presence described by students, such as feeling "present with the garment and fabric in some way," and "I get lost in the digital world", echoes Ingold's (2000) assertion that craft knowledge is deeply rooted in sensory memory.

Creativity

The integration of 3D learning tools like CLO into fashion education highlights the interplay between technology and creativity, revealing both opportunities and challenges for fostering innovation. CLO's exploratory and gamified features inspire creativity, but their potential is best realized through intentional and reflective use. Students who combined an open, experimental mindset with a strong foundation in traditional design demonstrated the most successful learning outcomes in 3D simulation software. This aligns with Diachent's (2010) perspective on design thinking, where creativity and practicality converge to address human needs through innovative solutions.

Creativity in fashion design, as defined by Sarkar and Chakrabarti (2011), involves generating novel and valuable ideas. CLO's features—such as fabric customization, avatar manipulation, and instant adjustments—serve as catalysts for this process by providing students with tools to iterate rapidly and explore a wide range of possibilities. One student remarked, "I like to change the different colors and textures of the fabric that I'm using," illustrating how CLO's digital fabric library sparks visual creativity. Another explained, "If I adjust this, I know that it's going to change the shape in 3D... I think it makes it a little easier to see it right away." These tools empower students to experiment with design elements in ways that traditional methods cannot.

This ability of the software to lower the perceived consequences of experimentation further encourages creativity. As one student noted, "The consequences for experimentation are a lot lower in CLO," which emboldens students to take creative risks without fear of wasting resources. This observation is consistent with Simmons and Ren's (2009) findings that individuals less focused on the risk of failure exhibit higher rates of creativity. Shen et al. (2018) similarly concluded that minimizing fear of failure fosters innovation and originality, as individuals more concerned with potential failure are less likely to engage in creative processes. However, this reduced risk can sometimes lead to impulsive decision-making, as evidenced by one student's reflection: "I saw that there was a velvet [fabric]... so I changed the whole outfit look to include the velvet instead." Empirical findings from other fields underscore the importance of personal traits and team dynamics in fostering creativity. For instance, Toh and

Miller (2015) observed that engineering teams with higher levels of conscientiousness, agreeableness, and tolerance for ambiguity were more likely to select novel concepts. This suggests that a supportive and open environment can further enhance the benefits of 3D learning tools in fashion education. CLO's ability to lower the perceived consequences of experimentation aligns with this idea, as it encourages risk-taking and exploration, essential elements in creative processes. These qualities of 3D simulation software provide unparalleled conceptual freedom as long as students have the technical knowledge. One participant noted, "I really like using [CLO] for conceptual things... to take it out of my head and actually put it somewhere." This capability enhances collaboration and feedback during critiques, as another student explained, "It makes it so much quicker for them to see... like, this is the way it's going to look... without actually seeing it on the body." Such features streamline the design process, allowing students to communicate their ideas more effectively.

Students who engaged the virtual environment through a lens of play, as a game-like tool displayed more creative initiative. One student reflected, "Yeah, I try to make it fun. I guess I also come up with that as, like a video game… looking at it that way helped me." Another compared CLO to an "expansion pack" of a video game, stating, "It was really exciting for me… now I'm actually creating everything from scratch." This playful mindset transforms design challenges into opportunities for exploration. The connection between play and creativity is well-documented; for example, Berretta and Privette (1990) found that children engaged in flexible play experiences demonstrated greater creative thinking than those involved in highly structured activities. Similarly, Russ (2010) identified play as a facilitator of insight and divergent thinking. As such, 3D simulation software integration into fashion education fosters creativity by lowering barriers to experimentation, enhancing conceptual freedom, and encouraging a playful approach to design, as long as a balanced pedagogical approach is taken: combining open exploration with a robust technical foundation and intentional reflection.

Expanding THREAD: Addressing Shortcomings

While the relevant tenets of the THREAD framework provided a valuable structure for analyzing and understanding design cognition in the virtual fashion design environment, the findings from this research revealed both its strengths and limitations. While THREAD effectively outlined four key tenets of design cognition—tacit knowledge, spatial visualization, haptic memory, and creativity, it did not fully encompass several critical dimensions of fashion thinking that emerged during the study. One notable limitation was THREAD's inability to account for emotional and motivational dimensions that go deeper than the creativity tenet, such as the playful exploration, emotional engagement, and flow states fostered by CLO's gamified interface. These factors proved crucial for fostering creativity, resilience, and a sense of immersion, which enabled students to deeply engage with their work. Yet, such emotional and motivational aspects are not explicitly captured within THREAD's structure. Additionally, the findings underscored the challenges posed by the absence of physical touch in virtual environments, which forced students to rely entirely on visual and cognitive memory of haptics. This limitation hindered their understanding of materiality and craftsmanship when not precedented with the proper physical pedagogical foundation.

Despite these limitations, THREAD remains a useful core framework for understanding design cognition in virtual fashion thinking. However, the findings suggest that it requires supplementation to fully capture the complexities of fashion thinking in digital contexts. Expanding THREAD to include emotional engagement and the mechanism to engage haptic memory would better address the hybrid nature of virtual design.

Limitations

The study's design posed limitations due to its scope and duration. The data collection occurred within two courses that allocated only four weeks to conceptual and physical prototyping before transitioning to virtual capsule development. This condensed timeline may have restricted students' ability to deeply engage with the 3D CLO software. Further, disparities in students' access to personal machines and varying levels of familiarity with the software may have hindered their capacity to demonstrate critical thinking fully. Compounding this limitation is the tacit and subconscious nature of much design knowledge, which students may not have been able to fully articulate during interviews. The interview methodology provided a valuable snapshot of participants' learning and cognition at a specific point in time. However, studying cognitive processes, such as creativity, problem-solving, and spatial reasoning, is inherently complex. Efforts to capture and articulate these processes face limitations in fully elucidating their multifaceted nature. Furthermore, demographic data were not collected, as they were not pertinent to the study's focus on cognitive processes within a virtual design environment. However, future research could examine how demographic factors influence engagement with THREAD, potentially offering deeper insights into variations in cognitive approaches across different student populations.

Conclusion

The findings of this study illustrated how virtual design environments facilitated by 3D simulation software, such as CLO 3D, profoundly shape the cognitive processes of fashion students, with each tenet of the THREAD framework's design cognition duality—Tacit Knowledge, Spatial Visualization, Haptic Memory, and Creativity—manifesting in a unique way. For example, Tacit Knowledge in virtual design was found to be deeply rooted in students' past experiences with physical toiles and engaged their intuitive design skills. Through a process of trial and error, students adapted to and navigated the digital interface, building this tacit knowing over time. This iterative learning was bolstered by 3D simulation software's rapid feedback mechanism, which accelerates experiential learning while reducing material costs associated with physical prototyping. However, over-reliance on trial-and-error methods in the absence of foundational physical design knowledge did sometimes lead to a superficial engagement with core patternmaking principles, which mat potentially limit students' technical understanding. The Spatial Visualization tenet emerged as students interpreted and constructed their designs through three-dimensional cognition, manipulating depth, scale, and proportion in 3D. Real-time interaction also enabled students to bridge the gap between virtual and physical design, testing and refining fit, movement, and form more fluidly than with physical materials. In conjunction with these affordances, it was also found that the intuitive ease of making rapid adjustments can sometimes discourage meticulous planning and critical evaluation, leading to impulsive design decisions that may compromise the coherence or feasibility of a final product.

Haptic Memory manifested in the 3D environment through students' sensory imagination and muscle memory. The interview data revealed that students experience an intuitive sense of physical presence within the virtual workspace. However, the lack of actual tactile feedback sometimes challenged students' ability to fully grasp the material properties and physical behaviors of fabrics. Creativity flourished in CLO's low-risk, high-reward virtual environment, where participants were found to explore with a heightened sense of freedom. Student designers expressed the creativity tenet through experimentation, where customization, instant visualization, and avatar manipulation facilitated an immersive flow state. On the downside, the gamified nature of the software did lead some students to prioritize aesthetic experimentation over practical considerations. In summary, the virtual fashion design environment serves as both a transformative and nuanced tool in fashion education, offering unparalleled opportunities for experiential learning, creative exploration, and design iteration. While its affordances do foster some design skills, its drawbacks highlight the importance of balance: virtual experimentation should be coupled with a robust foundational education in the physical environment and critical reflection to ensure fashion thinking.

CHAPTER 4 REFERENCES

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CHAPTER 5: CONCLUSION

The three-article dissertation presented a robust exploration of fashion thinking within the larger domain of 3D simulation software in design. By synthesizing theoretical frameworks and empirical assessments, this dissertation offered insight into the multifaceted nature of fashion design in the virtual environment. The foundational work laid out in the first paper set the stage for subsequent investigations by proposing the THREAD model, a disciplinary framework derived from a meta-narrative literature review. The THREAD model aims to address the instability of the fashion thinking concept (Petersen et al., 2016). This framework not only addresses the critical gap identified in the existing literature in understanding of fashion thinking but also provides a systematic lens through which to analyze and interpret critical thinking and design cognition within virtual fashion design pedagogy.

Transitioning from theory to practice, the second paper empirically explored critical thinking in the virtual environment among undergraduate fashion design students. Contextualized in the environment of Industry 4.0 and through the application of the think-aloud protocol, this study delved into the cognitive processes involved in virtual design, thereby shedding light on the efficacy of digital tools in fostering critical thinking abilities. The third paper explored the intricacies of fashion design cognition within the virtual environment by employing semi-structured artifact interviews to unravel the specific cognitive processes and strategies utilized by fashion designers when creating within 3D simulation software. This paper aimed to formalize and capture the knowledge embedded within the praxis of virtual fashion design.

Collectively, these three articles contribute significantly to our understanding of fashion thinking in the realm of virtual design. By addressing different facets of 3D fashion thinking from various angles, this dissertation not only fills critical gaps in the literature but also informs pedagogical practices, design processes, and industry practices. The interdisciplinary approach employed underscores the importance of integrating theoretical frameworks with empirical investigations to advance our understanding of fashion design in the digital era. As the fashion industry continues to evolve in the era of Industry 4.0, where digital technologies are reshaping traditional manufacturing and design processes (Benešová & Tupa, 2017; Cabrita, Safari, & Dueñas, 2020), the findings from this dissertation have significant implications for preparing future designers for the demands of the industry. In conclusion, the three-article dissertation represents a significant contribution to the field of fashion design, offering a comprehensive understanding of fashion thinking within the context of 3D simulation software. By bridging theory and practice, this dissertation not only advances scholarly knowledge but also informs pedagogical practices and industry strategies.

This chapter explores the overarching implications from the three-article dissertation, focusing on how the findings from the empirical studies elucidated critical thinking and design cognition in the 3D environment, capturing and discussing the knowledge found to be embedded within the praxis of virtual fashion design. This chapter then examines THREAD's conceptualization of fashion thinking as a duality comprised of critical thinking and design cognition, and how the tenets within each category held up to scrutiny, discussing the proposed expansion of the model to better align with study findings. Revisions to THREAD address its shortcomings, with key updates to the design cognition and critical thinking dualities. The chapter also outlines delimitations and how findings address gaps in the literature, positioning the updated THREAD model as a framework for evaluating fashion thinking in virtual design. Finally, the chapter concludes with forward-looking strategies for preparing future designers to navigate hybrid virtual-physical modalities effectively as the industry strides forward towards the 4th revolution.

Three Article Dissertation Insights

This dissertation research examined how virtual environments impact fashion thinking through two dualities: critical thinking and design cognition. Findings from the dissertation as a whole revealed that virtual tools function as an extension of existing practices, revealing the hybrid nature of 3D fashion thinking, the novel cognitive adaptations required for material perception, and the evolving role of creativity in a gamified digital space.

3D Fashion Thinking is Hybrid

The rise of virtual design tools like CLO has changed how fashion is created, but not by replacing traditional skills—instead, it has reshaped how those skills are used. Rather than a one-way shift from physical to virtual design (and vice versa), this research showed that competent designers move fluidly between both worlds in a continuous loop. For example, a designer may start by draping fabric on a dress form to understand the fabric behavior in various drapes, then translate that knowledge into a 3D simulation to refine the silhouette and test pattern variations. Later, they might return to physical prototyping after digitizing the virtual patterns to assess fit in real life. This hybrid workflow allows for deeper experimentation and precision, but it also means that designers must develop the ability to navigate both physical and virtual spaces seamlessly.

This challenges the notion that 3D tools are an alternative method to traditional design. Instead of replacing draping, patternmaking, and sewing, digital tools expand on and supplement these processes, offering new ways to iterate and refine ideas. For instance, students learning garment construction might first explore design possibilities in a virtual environment, where they can quickly test proportions and fit without wasting physical materials and once settled on a solution, move to physical. This highlights the importance of integrating virtual and physical learning from the start rather than treating 3D as a separate or optional skill. As fashion education adapts to these changes, it must embrace a multi-modal approach, where students are encouraged to think across both dimensions. This means not only teaching traditional craftsmanship alongside virtual proficiency but also fostering the critical thinking skills needed to transition between the two. The future of fashion is not purely physical or virtual—it is a dynamic blend of both, where each informs and enhances the other in ways we are only beginning to understand.

Novel Cognitive Strategies for 3D Haptics

Traditionally, fashion designers have relied on physical touch to understand material behavior—how fabrics drape, stretch, fold, and react to manipulation. However, in virtual design spaces, materiality is no longer defined solely by hands-on experience. Instead, designers must rely on a combination of cognitive recall of past physical experience and visual interpretation to assess fabric properties. This means that when working in 3D software like CLO, designers are engaging with materiality in a different way, using digital simulations and memory rather than direct touch. For example, a designer who has previously worked with silk in a physical setting may instinctively know how it should behave and look in a digital environment, adjusting the digital fabric properties in the property editor by applying normal and roughness maps and toggling warp-weft-shear amounts, to achieve an accurate simulation.

Designers must develop and employ alternative cognitive strategies, using perceptual adaptation, sensory imagination, and real-time iteration to make up for the absence of touch. This suggests that in 3D, fashion thinking manifests as an abstract mode of thinking, where designers anticipate material behavior rather than directly feeling it. Findings from this dissertation suggested that students use perceptual adaptation in 3D—adjusting their thinking to interpret fabric behavior based on visual cues, past experience, and predictive reasoning. This shift suggests that fabrics education must evolve beyond physical touch and textbook-based material science. Cross-modal sensory training—such as re-creating the fabrics in 3D programs (Shima Seiki for knits and CLO for wovens) alongside touching and learning about their properties in real-life—could help designers build a more comprehensive understanding of fabrics in both virtual and physical spaces. Pairing real-world fabric swatches with learning how to create their virtual counterparts could teach students how to recognize the nuances of weight, stiffness, luster, hand, and drape regardless of modality. As technology progresses, traditional ideas of textile engagement will continue to be challenged. While physical experience remains invaluable, virtual environments are reshaping how designers understand materials, expanding the definition of materiality beyond touch alone.

Gamification Reshaping Creativity

When designers who possess mastery of the software and design/patternmaking workflows alike use 3D tools like CLO, they are not just designing—they are playing. These tools provide instant feedback, quick undo options, and visually polished results, making the design process feel more like a game than traditional hands-on garment construction. This game-like experience was found to influence how designers make decisions in both positive and challenging ways. On one hand, gamification encourages creativity by enabling rapid experimentation, where designers can quickly test ideas, change materials with a click, and instantly visualize results. The ability to undo mistakes with no real-world consequences fosters a low-stakes environment, allowing for risk-taking and unconventional thinking. Additionally, the interactive, immersive nature of 3D design software can engage designers in deep flow states, where they become fully absorbed in the creative process.

However, gamification was also found to limit deeper design thinking by sometimes prioritizing surface-level aesthetics over functionality. Because digital tools generate professional-looking renderings so quickly, designers focused more on how garments appeared on-screen rather than how they would function or be constructed in real life. Over-reliance on algorithmic features, such as auto-generated walking and seam reversal and preset material properties bundled in the fabric file were found to reduce hands-on problem-solving for some students in the study. The instant, clickable nature of digital design was also found to encourage designers to cycle through options rapidly, where students made decisions based on convenience and aesthetics rather than thoughtful consideration. While gamification expands creative possibilities, fashion pedagogy must ensure that critical thinking, technical expertise, and a robust foundation in fabric science remain essential components of the creative process.

Understanding Reflection in 3D Design

The research found that while virtual tools enable fast experimentation, they do not automatically encourage designers to pause and critically assess their decisions—unless reflection is deliberately built into the workflow. For example, a student working in CLO might quickly cycle through various sleeve shapes or fabric textures without taking the time to evaluate how each change impacts the garment's overall function, pattern efficacy, or ties back to the design collection's direction. Without structured moments of reflection, designers risk making decisions based on what looks visually appealing in the moment rather than considering the long-term design intent and integrity of the patterns. The dissertation findings revealed that the students those who engaged in strategic reflection, which often looked like revisiting their CADs and fashion illustrations to compare, or stopping to pause and think before making decisions, demonstrated a stronger connection between their virtual decisions and their broader creative vision for their collection.

This suggested that fashion education should integrate intentional reflection points for balance. This might look like requiring designers to document key iterations and explain their thought processes, much like sketchbook annotations in traditional design. By embedding reflection into digital workflows, designers can maximize the benefits of rapid iteration while ensuring that each decision contributes to a thoughtful and cohesive design process. As fashion education adapts industry 4.0, a balanced approach that integrates technical proficiency, perceptual adaptation, and reflective practice will be essential in preparing designers for the future of virtual and hybrid workflows.

Delimitations

In terms of delimitations, the theoretical study deliberately focused on defining critical thinking and design cognition within a 3D fashion thinking context, offering a clear theoretical scope for the THREAD framework. By targeting educational applications, specifically within virtual fashion design learning environments, the study aligned with the growing emphasis on digital pedagogy in the discipline. The THREAD framework was positioned as a starting point for iterative refinement and future empirical investigations, ensuring its adaptability to new insights and technological advancements. The centrality of 3D simulation software in the study provided an initial pathway for integrating digital tools into fashion design pedagogy, acknowledging its relevance in preparing students for industry demands. While it lacked empirical testing within this particular article, the study emphasized framing critical thinking and design cognition as dual pillars of fashion thinking in a 3D design context, serving as a theoretical groundwork for subsequent research.

Article 2 intentionally focused on the tenets of problem-solving, reflexivity, and individual agency, narrowing its scope to provide deeper insights into critical thinking within the larger concept of fashion thinking. Additionally, the study's focus on online studio courses aligned with the increasing importance of digital pedagogy, especially as it is conducive to virtual learning and software. Sampling upper-level students in these online settings enabled the research to investigate critical thinking within the innovative virtual design environment, beyond mere software interface learning, ensuring its alignment with the evolving landscape of fashion design education.

Like article 2, this third article intentionally focused on certain tenets of the THREAD model that aligned with design cognition: creativity, haptic memory, spatial visualization, and tacit knowledge. This strategic delimitation narrowed the scope of the study to provide deeper insights into design cognition within the larger concept of 3D fashion thinking. In the same way as Article 2, this study's focus on online studio courses aligned with the growing emphasis on digital pedagogy, particularly its suitability for virtual learning and software integration. Sampling upper-level students in these settings allowed for an exploration of design thinking within the innovative virtual design environment, moving beyond software interface learning to address the evolving needs of fashion design education.

Filling Gaps in Literature

The above discussed dissertation findings addressed critical gaps in the literature by offering a nuanced perspective on how fashion thinking manifests in the virtual design environment. One significant gap lay in the tendency of previous research to treat fashion thinking as a blanket term, without addressing a certain necessary duality or the aspects that underpin it. Previous studies purport that fashion thinking is a spinoff of design thinking (Nixon & Blakely, 2012; Dieffenbacher, 2020; Petersen, MacKinney-Valentin, & Reigels Melchior, 2016). There are no other studies that explore fashion thinking in the context of 3D simulation software, though one very recent study explored the intersection of 3D design knowledge with creativity (Papchristou & Zolota Tatsi, 2024).

This dissertation reframed fashion thinking as a duality and integrated cognitive process, demonstrating how design cognition and critical thinking, each comprised of their corresponding tenets, are deeply interconnected and necessitated in the 3D fashion environment. Another key gap addressed was the disconnect between physical and digital skills in existing fashion studies, which often consider these competencies in isolation. The findings underscored the critical role of foundational physical skills, such as patternmaking and garment construction, in enabling success with CLO. This highlights the need for hybrid pedagogical approaches that integrate physical and virtual design training, ensuring that digital tools enhance, rather than replace, the precision and intentionality cultivated through hands-on experience.

The study also explored the depth and limitations of reflexivity in the virtual fashion design environment, addressing a gap in how strategic reflection is conceptualized. While real-time feedback in CLO fosters rapid problem-solving and immediate reflexive design adjustments, it can also encourage reactive decision-making, potentially limiting students' engagement with broader design principles and techniques of patternmaking and draping. Additionally, the research redefines creativity as emergent in gamified virtual environments that facilitate the mindset of play, addressing a gap in the literature that often prioritizes technical mastery over the emotional and exploratory dimensions of design (Wiana, 2018; Conlon &

Gallery, 2023). CLO's gamified interface promotes creativity and flow states, transforming design challenges into opportunities for discovery. Overall, this study builds on previous research by offering a more detailed analysis of how design cognition and critical thinking intersect to manifest fashion thinking in virtual environments.

While existing studies show a link between 3D simulation software for fashion design in improving students' skill development (Baytar, 2017), spatial cognition (Park, Kim, & Sohn, 2010), creativity (Papchristou & Zolota Tatsi, 2024), this study aimed to uncover how fashion thinking manifests in the 3D environment as a whole. This research provides an understanding of how tacit knowledge, spatial visualization, problem solving, creativity, individual agency, haptic knowledge and reflexivity operate in tandem within the 3D fashion design process.

THREAD: Evaluating the Duality of Fashion Thinking in Virtual Design

The findings highlighted that the THREAD model's design cognition and critical thinking operate as interconnected and complementary dimensions of fashion thinking within the context of virtual fashion design pedagogy. Design cognition provided the technical foundation to navigate digital tools, while critical thinking enabled students to reflect, innovate, and optimize within the software's capabilities. For instance, a tacit understanding of fabric drape or construction principles (design cognition) must work in tandem with reflective, iterative practices (critical thinking) to produce designs that are both aesthetically cohesive and functional. This interplay was particularly evident in CLO's immersive and gamified features, which encourage intuitive experimentation (design cognition) while requiring critical analysis of real-time feedback to refine designs.

As fashion design increasingly integrates virtual tools, the ability to synthesize traditional skills with innovative digital approaches becomes paramount. Students must adapt foundational knowledge to digital contexts, justify their design decisions with critical reasoning, and innovate within the constraints of virtual environments. This framework highlighted that successful virtual design is not merely a technical or creative endeavor but a holistic practice that integrates both intuitive and analytical thought processes. While this duality promoted a richer understanding of design, it also exposes potential weaknesses, such as the risk of over-reliance on intuitive or technical elements without sufficient critical reflection, suggesting the need for balanced pedagogical strategies.

Expanding THREAD: Addressing Shortcomings

While the THREAD framework provided a valuable structure for analyzing and understanding design cognition and critical thinking in virtual fashion design environments, the findings from this research revealed both its strengths and limitations. While THREAD effectively outlined seven key tenets—tacit knowledge, spatial visualization, haptic memory, creativity, problem-solving, reflexivity, and individual agency—it did not fully encompass several critical dimensions of fashion thinking that emerged during the study, hence the updates to the THREAD model (Table 5.1).

Table 5.1

Revised THREAD Model of 3D Fashion Thinking

Dimension	Tenet	Description
Design Cognition *(How designers perceive, process, and create in virtual environments)*	**Tacit Knowledge**	Implicit, experience-based understanding of design principles and workflows.
	Haptic Memory and Material Perception	Differentiating between the cognitive recall of physical touch and the challenges of material engagement in digital contexts
	Creativity and Playful Exploration	Open-ended experimentation and gamification in 3D design.

Dimension	Tenet	Description
	Spatial Visualization	The ability to mentally and digitally manipulate 3D forms.
	Emotional and Motivational Engagement	The role of intrinsic motivation, immersion, and flow states in sustaining creative momentum.
Critical Thinking *(How designers reflect, analyze, and problem-solve in virtual environments)*	**Individual Agency**	The ability to make autonomous, intentional design choices.
	Reflexivity *(Two Levels*	**Reactive Reflection** – Immediate, real-time adjustments in response to feedback. **Strategic Reflection** – Connecting iterative changes to broader design principles and long-term goals.
	Problem Solving	The integration of logic, adaptability, and creative troubleshooting in digital workflows.
	Perceptual Adaptation	The shift in thinking required to compensate for the absence of physical touch, translating material understanding into virtual workflows.

Key Updates to Design Cognition Duality

The design cognition dimension of the THREAD model was updated to better capture the nuanced ways designers think, create, and engage in virtual fashion environments. The key updates (Table 5.1) reflect findings that highlight gaps in the original model, particularly in relation to material perception, playfulness, and emotional engagement.

Haptic Memory to Haptic Memory and Material Perception

In the original THREAD model, haptic memory was treated as a singular concept, representing how designers recall and apply past tactile experiences when working with materials. However, research findings revealed that digital environments, where physical touch is absent, require designers to engage in an additional layer of cognitive processing. Rather than simply recalling how a fabric feels, they must actively translate that knowledge into visual and digital cues to approximate material properties within the virtual space. This reliance on prior tactile experience presents a challenge, particularly for students or designers with limited hands-on fabric interaction, as they may struggle to accurately predict how materials will behave digitally.

Without the ability to physically manipulate fabric in real time, designers must develop strategies to compensate for the lack of sensory feedback. Designers must engage in perceptual adaptation, reinterpreting their haptic memory using visual cues, system-generated data (such as fabric tension maps), and trial-and-error adjustments within the software. This process demands a shift in thinking, where material perception becomes an active cognitive skill rather than only a passive recall of past experiences. By revising haptic memory into haptic memory & material perception, the updated THREAD model better reflects the dual nature of material engagement in virtual environments. It acknowledges that designers must not only recall past tactile experiences but also develop new cognitive strategies to assess and interact with digital representations of materials. This update highlights the need for integrating physical fabric studies with digital tools to bridge the gap between tactile intuition and virtual design workflows, ensuring that designers can translate and apply haptic memory.

Creativity to Creativity and Playful Exploration

The revision from creativity to creativity and playful exploration reflects a deeper understanding of how creativity was found to function in virtual design environments. Traditionally, creativity has been associated with ideation—the ability to generate original ideas and innovative solutions. However, research findings highlighted that in digital platforms like CLO, creativity is equally driven by exploration and experimentation within a gamified environment. The interactive nature of CLO’s interface allows designers to engage in trial-and-error processes with minimal consequences, encouraging them to take risks, iterate freely, and discover unexpected design solutions. This playful engagement fosters a sense of immersion and flow, where designers feel motivated to push boundaries and refine their work dynamically.

By integrating playful exploration into the concept of creativity, the revised THREAD model acknowledges that digital tools do not just support creativity—they actively shape how designers think and work. Unlike traditional methods, where physical constraints like fabric waste or construction limitations may inhibit experimentation, CLO provides an open-ended, reversible space where designers can manipulate materials, test variations, and refine forms instantaneously. This encourages a mindset of discovery, where mistakes become learning opportunities rather than setbacks. The revision underscores the role of play as a cognitive driver in digital design workflows, positioning it as a key factor in and presentation of creativity.

New Addition: Emotional and Motivational Engagement

The addition of the tenet emotional and motivational engagement to the THREAD model acknowledges the psychological and affective dimensions of virtual fashion design, which were previously overlooked. The original model focused on cognitive and technical aspects of the design process but did not account for the ways intrinsic motivation, emotional investment, and immersive experiences play a role in design cognition. Research findings revealed that designers working in digital environments like CLO often enter flow states—a psychological condition where they become deeply absorbed in their work, losing track of time and external distractions. Incorporating emotional & motivational engagement as a tenet into the design cognition category of the model highlights that successful digital fashion design is not just about skill or technical proficiency but also about maintaining motivational momentum through emotional engagement. When designers feel emotionally connected to their work, they are more likely to persist through challenges, take creative risks, and push the boundaries of their designs. The gamified nature of CLO, with its interactive and intuitive features, enhances this heightened sense of emotional engagement, reinforcing motivation. By recognizing the impact of emotional and psychological factors in virtual design workflows, this addition ensures that the THREAD model more accurately reflects the realities of digital fashion creation.

Key Updates to Critical Thinking Duality

The critical thinking duality in the THREAD model was updated (Table 5.1) to better account for the complexities of reflective and analytical processes in virtual design environments. In the original model, critical thinking was framed through individual agency, reflexivity, and problem solving. While this structure captured key aspects of decision-making, approach to challenges, and reflection, it did not fully differentiate between levels of reflective thought or the perceptual shifts required when transitioning from physical to virtual fashion design.

Levels of Reflexivity

The revision of reflexivity into two distinct levels—reactive reflection and strategic reflection—better articulates the nuanced ways designers engage in reflective thinking within virtual environments. Reactive reflection refers to immediate, real-time adjustments made in response to system feedback, such as troubleshooting errors, refining garment simulations, or modifying digital patterns based on direct visual cues. This type of reflection is fast, instinctive, and often driven by the interactive nature of CLO. In contrast, strategic reflection represents a more deliberate and intentional thought process in which designers connect iterative changes to broader design and patternmaking principles or their design concept. By expanding reflexivity into these two levels, the revised THREAD model captures the full spectrum of reflective engagement, addressing a key limitation of the original framework, which treated reflexivity as a singular concept with only one way of presenting. This distinction ensures a more accurate representation of how designers navigate digital workflows, balancing immediate problem-solving with deeper conceptual thinking.

New Addition: Perceptual Adaptation

The introduction of perceptual adaptation as a new tenet within the critical thinking domain acknowledges the cognitive shift required when working in a digital space where physical touch is absent. Unlike haptic memory, which falls under design cognition and refers to recalling past tactile experiences, perceptual adaptation is about the active mental processes needed to reinterpret and translate physical design knowledge in virtual workflows. In traditional fashion design, designers rely on direct physicality and haptic feedback to assess fabric weight, texture, and behavior, as well as to manipulate patterns in a hands-on manner. However, digital platforms like CLO remove this sensory dimension, requiring designers to translate material understanding and patternmaking logic into visual and computational cues.

Research findings revealed that students who lacked a robust prior experience with in-person design and pattern manipulation struggled significantly more in virtual environments, as they had fewer physical reference points to guide their decision-making. This challenge extended beyond fabric evaluation to include pattern development, garment construction, and fit analysis, all of which traditionally depend on spatial and tactile problem-solving. Without the ability to drape fabric on a dress form, manually true patterns, or feel material resistance, designers have to engage and translate differential cognitive strategies in the 3D environment. This new tenet highlights the mental recalibration necessary to compensate for the lack of direct tactile and physical engagement, making it a critical component of the duality of critical thinking within digital fashion thinking.

Action Forward: Preparing Future Fashion Designers

The findings underscored several critical pedagogical implications for preparing future designers to meet the evolving demands of the fashion industry. First, the sequence of curricular offerings is essential. Foundational, and perhaps advanced, courses in flat patterning and draping should precede the introduction of 3D simulation tools. This progression will allow students to develop the tacit knowledge required for virtual proficiency by grounding their skills in physical techniques. Second, it is important to embed reflective strategies within the curriculum to foster deeper engagement and critical thinking that focuses on the strategic reflection over reactive reflection, as discussed. Encouraging and requiring students to document their design processes in a design journal, analyze decisions made in virtual environments in a reflexive log, and participate in critiques that center on virtual design would cultivate a more intentional design approach. These practices mirror industry expectations, where designers are required to justify every choice made, respond to feedback, and iterate on their designs collaboratively. Reflection, when structured effectively, ensures that students not only understand the "how" of their design decisions but also the "why."

Third, CLO's instant visualization tools present a unique opportunity to support sustainable design practices. By enabling rapid prototyping in a virtual environment, students can experiment with unconventional ideas and techniques without fear of wasting physical materials. The affordances of this tool should be expanded into "zero waste" lessons where students can be brough to understand analytical and sustainable pattern-making functions in conjunction with a software that supports that initiative. Lastly, the findings revealed that fostering a mindset of play and exploration within virtual environments enhanced creativity and resilience. Viewing CLO as an interactive and dynamic tool, rather than a purely technical one, will help students approach design challenges with curiosity and adaptability. Assignments that emphasize open-ended experimentation and encourage students to integrate personal values or cultural aesthetics may provide opportunities for students to connect their designs to meaningful narratives. In conclusion, preparing future designers requires a pedagogical approach that integrates foundational physical skills, reflective practices, more advanced sustainable patternmaking methods, and exploratory learning.

Conclusion

This three-article dissertation has provided a comprehensive examination of 3D fashion thinking in the digital era, highlighting how 3D simulation software shapes both critical thinking and design cognition. By bridging the conceptualization of a novel theoretical framework with empirical research, this work has solidified the THREAD model as a foundational tool for understanding 3D fashion thinking as a duality—much like a two-ply yarn, where critical thinking and design cognition are twisted together to form a stronger, more resilient whole. Just as plying strengthens individual fibers by intertwining them, the interplay between these dimensions reinforces a designer's ability to navigate the virtual design space fluidly.

Through its evolution and refinement, THREAD has demonstrated its applicability in evaluating and guiding the understanding of virtual fashion pedagogy, offering a structured lens through which educators and designers can navigate the rapidly evolving digital landscape. Much like how different fiber blends impact the final properties of a yarn, the balance of design cognition and critical thinking may vary across different designers and learning contexts—but both strands remain essential for a durable and adaptable practice. Ultimately, this dissertation underscores the importance of preparing future fashion designers to seamlessly integrate physical and digital methodologies. As Industry 4.0 continues to redefine the boundaries of design, fashion education must embrace hybrid approaches that merge traditional craftsmanship with digital innovation. This research lays the groundwork for a more adaptive, reflective, and forward-thinking generation of designers—equipped to thrive in the evolving industry landscape.

CHAPTER 5 REFERENCES

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APPENDIX A

Interview questions: Decoding the Abstract: 3D simulation software and fashion design cognition

These questions aim to extract detailed and reflective responses from students, archiving the cognitive processes and strategies engaged when designing in the virtual environment.

Tacit Knowledge Application

1. How has your past experience in patternmaking and design collection development, including specific courses or learning experiences, influenced your adaptation to CLO?
2. Did you rely on intuition or gut feelings during the 3D design process? If so, how?
3. Did you encounter design challenges in CLO that are hard to describe? [Probe for design principles/design methods]

Spatial Visualization

1. Can you discuss the techniques and tools you utilized within the software interface, such as the gizmo tool, to manipulate and navigate the virtual environment?
2. How did your experience with physical three-dimensional prototypes impact your utilization of the 3D simulation software? [Probe: How did you ensure proportionality across the patterns]

Haptic Memory

1. Has your experience with physical fabrics influenced how you interact with materials in CLO, particularly in terms of texture, movement, selection, and drape?
2. How well do you think the software can mimic the feeling of touching different fabrics?
3. When you're designing, how much does it help to see instant changes in how your design looks on the screen?

4. How do your hand movements relate to what you see on the screen when you're designing in CLO, and how does muscle memory affect your design workflow? [probe with pulling gesture as an example]

Creativity

1. How did you showcase your own design initiative, aesthetic, and stylization with your design decisions while using the 3D simulation software?
2. Were there instances where you felt constrained or empowered in expressing your individual designer style and preferences through the software?
3. Did CLO have any particular features that inspired innovative solutions or sparked new creative ideas?
4. Can you provide examples of how your personal designerly touch was incorporated into the virtual design process?

APPENDIX B

Journals

International Journal of Clothing Science and Technology

Paper 2 (Empirical): Fashion Thinking in Industry 4.0: Assessing 3D simulation software and undergraduate fashion design students' development of critical thinking skills.

Impact factor 1.15

Emerald Publishing

6-14 pages

60 days avg. from submission to first decision

Scope:

- Automatic, Intelligent systems and robots
- Computer-aided design and manufacture
- Modelling of materials and processes
- 3D Modelling, design and visualization

Fashion Theory

Paper 1 (Theoretical): Fashion Thinking in the virtual environment: Towards a Novel Disciplinary Framework for Pedagogical Design

Impact Factor: 1.0

Taylor and Francis Publishing

71 days avg. from submission to first decision

16% acceptance rate

Maximum of 10,000 words for theory paper

Scope:

- Fashion as critical discourse and analysis

Journal of Textile Engineering & Fashion Technology

Paper 3 (Empirical): Decoding the Abstract: 3D simulation software and fashion design cognition

Time to publication: 4-5 weeks

Publisher: MedCrave Publishing

Impact Factor: 1.25

Editor in Chief: Dr. Hahn @ Kent State University

Scope:

- Recent advancements in fashion technology all over the globe.
- Apparel Manufacturing Technology
- Application of Computers in Textile and Fashion Development

APPENDIX C

Timeline

Proposal Hearing: June- August 19th (Classes begin)

September 23rd: IRB approval by this date

September 23rd - October 28th: Data Collection

September 2nd- October 28th: RMCAD Fashion Design III + Graduate Portfolio, Fashion Design II and Product Development runs (CLO begins Week 4)

October 28th- December 27th: Data Analysis + write up results and discussion:

December 30th- January 31st: Final Edits on Dissertation

February 8th: Deadline to apply to graduate

By January 31st: send out Defense When2Meet

February 3rd-February 28th: Defense

March 21st: GS24 Report of Final Examination Form Due

March 28th: GS30 Dissertation Submission Form- must have all required signatures.

• Survey of Earned Doctorates Certificate of Completion (uploaded to the GS30 form and required for doctoral recipients)

• If applicable, include ETD Embargo Restriction Request (GS30 Embargo Section)

• Last Day to Submit Electronic Thesis or Dissertation (ETD) in ProQuest

April 4th by 4:45 pm MT: ETD formatting approval from Grad School

• ETD formatting must have final Graduate School approval – all revisions must be complete and approved in ProQuest

• ETD processing and approval is only available during Graduate School business hours - business hours end at 4:30 p.m. MT