THE VIRTUAL BODY

IN IMMERSIVE VIRTUAL REALITY

AND ITS INFLUENCE ON CREATIVITY

By

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"*Jump! Some floor will appear.*" That was the phrase my father told me when my family and I started this adventure four years ago. Now, after many hours of hard work, I can give thanks to God for permitting us to complete this journey.

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I want to close with a phrase a good friend of mine told me one time: "*The harder I work, the luckier I get.*" Thanks, OSU, for this opportunity. I will always be a cowboy in the depth of my heart.

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Title of Study: THE VIRTUAL BODY IN IMMERSIVE VIRTUAL REALITY AND ITS INFLUENCE ON CREATIVITY

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Abstract: The relationship between the design process, its multiple stages, and how different design mediums affect this process continues to be a topic for research and exploration. The selection of different design tools is done according to the characteristics of the multiple stages within this process. Multiple studies have argued that digital media tools are still incapable of supporting idea development in conceptual stages, but digital mediums have evolved, and digital tools are present in the design process from the beginning to the end. Current digital mediums can provide immersive characteristics in virtual environments that increase the user's sense of presence and embodiment, affecting cognition. Thus, there was a critical need to evaluate and explore how new digital media with multiple levels of embodiment can affect creativity and learning outcomes in conceptual ideation stages of the design process.

In addition to presence and embodiment, creativity and spatial abilities are crucial elements for designers. The primary objective of this study was to assess creativity and spatial abilities, examining three different levels of embodiment (first-person online virtual body [VB], first-person offline VB, and third-person online VB). Participants were randomly assigned to one of the three conditions and were required to solve a design task. Pre and posttest questionnaires were used to collect data in addition to a psychophysiological device to account for cognitive load. Spatial skills were assessed before and after the intervention, and the designed outcomes were evaluated to measure the level of creativity. The central hypothesis was that the higher the sense of embodiment (SoE), the greater the presence and lower the cognitive demand of the system, which can be used to improve spatial abilities and stimulate creativity.

This study explored how creativity of the designed outcomes and spatial abilities were affected by different levels of embodiment. This study provides relevant information on how VR environments positively affect the development of spatial abilities. Also, the findings facilitate discernment in how different VR setups affect cognitive load on participants, which may ultimately affect cognition and creative thinking.

Keywords: immersive virtual reality, design process, virtual body, cognitive load, functional near-infrared spectroscopy

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CHAPTER I

INTRODUCTION

Archer (1965) paved the way for researching the design process, and it was further explored by multiple researchers who have strived to better understand the way designers think, develop their proposals, and yield design outcomes (e.g., Cross, 1982; Darke, 1979; Goldschmidt, 1991; Suwa et al., 1998; Tang & Gero, 2002). With new design mediums emerging on a regular basis, there is still much open for research within this realm . According to Gericke and Blessing (2011), there is no definitive methodology for the design process, given the range of different proposals between different models. However, multiple shared stages in those models have been demarcated (Gericke & Blessing, 2011). These stages are subdivisions of the design process, often referred to as *design phases*. The three most commonly identified main stages are a *problem definition stage*, a *conceptual design stage,* and a *detail design stage* (Gericke & Blessing, 2011). Each stage requires different tools comprising diverse design mediums, which will vary according to the needs of the designer as well as the specific stage's properties (Ibrahim & Rahimian, 2010; Rahimian et al., 2011). However, multiple researchers have argued that digital media tools are still incapable of supporting idea development in conceptual stages (e.g., Bilda & Demirkan, 2003; Kwon et al., 2005; Meniru et al., 2003; Stones & Cassidy, 2007). The issue is that digital medium tools evolve rapidly. According to Yu et al. (2013), the usage of digital medium tools in the design industry has changed, but they seem to be restrictive for ideation purposes (e.g., Bilda & Demirkan, 2003; Kwon et al., 2005; Meniru et al., 2003; Stones & Cassidy, 2007). Moreover, digital tools have replaced traditional tools in different design practices (e.g., Hernandez, 2006; Yu et al., 2013).

Digital technology and the use of computers has become a part of our everyday lives. Nowadays, individuals live in a blended space between reality and technology, defined as *ubiquitous computing,* in which interaction with digital media occurs on a daily basis (Dourish, 2001). Ubiquitous computing has become part of our day-to-day activities through the use of digital devices such as smartphones, computers, and tablets. Individuals face a world in which they interact with such devices consciously, such as when they grab a smartphone to search for something on Google, or unconsciously, such as when they interact with a microwave to heat a meal (Verbeek, 2005). Besides, the younger generation lives in a world post-1998, the year in which Google was launched, and have known only life with Google, filled with digital devices and digital interactions (Dourish, 2001). Design students are not exempt from this reality and higher education must adapt to such conditions. Given the way design students today interact with the world and understand the design process, the discipline must move away from restrictive visions by which digital tools were previously labeled (Purcell & Gero, 1998).

A crucial improvement in human interaction with technology using digital devices resides in the concept of *transparency*, understood as the ability of the interface to fade into the background (Verbeek, 2005; Winograd & Flores, 1986). Higher levels of transparency result in more natural ways to interact with the immediate surroundings. This innate behavior relates to the individual's sensation of control of their actions consciously or unconsciously (Ahn et al., 2014). A combination between high transparency and high sensation of control in an interaction will support *embodiment* in the individual (DeSutter & Stieff, 2017), as explained in Dourish's own words, "Embodiment is the property of our engagement with the world that allows us to make it meaningful" (2001, p. 126). The design process is no exception to this digital interaction outburst. New digital tools permit deeper thought processes, positively affecting the design process (Hernandez, 2006). Also, the increase of transparency, allowing more "natural" (embodied) actions, has opened up opportunities for digital mediums to evolve and become more intuitive to satisfy the designer's needs. Given that the evolution of digital tools permits their use throughout the design process (Shih et al., 2017), it is necessary to research how these may affect such a process. More specifically, digital mediums have been seen as restrictive in phases of the design process, such as the conceptual design stage (idea generation).

Aiming to diminish this gap, this study selected immersive virtual reality (IVR) as the platform representative of a digital medium, to assess its possibilities to elicit idea generation (creativity). Virtual reality (VR) was selected, as it permits *situatedness* of the user in a virtual environment that brings the user into the realm of the digital medium, stepping away, but similarly to the physical world (Anderson, 2003). This situatedness of VR is of critical importance because it mimics the way human beings interact with the world to obtain knowledge and increase their cognitive processes (Clark, 1998; Hilditch, 1997). Moreover, VR permits active experimentation controlling external aspects that can affect the variables (Wang et al., 2015). This study assessed one variable defined as sense of embodiment (SoE) within three different levels of a virtual body (VB). The concept of the VB has been understood as a variation between online and offline modalities of body representation (Carruthers, 2013), as a critical element for immersion (Slater et al., 2010), as transference of the real body to a virtual environment (Slater et al., 2010), and even as a modifier to the perception of the real body (Serino et al., 2016).

Kilteni et al. (2012) defined SoE as "the ensemble of sensations in conjunction with being inside, having, and controlling a body, especially in relation to VR applications" (p. 374). A working definition of SoE comprises three subcomponents: self-location, sense of agency, and sense of body ownership (Kilteni et al., 2012). The VB relates to the self-recognition of a given subject within a virtual environment. Also, the VB can be divided into online and offline representations. In the former, the body is somehow present either partially or totally, whereas in the latter, there is no visual perception of the body, but there is a connection with it, similar to the effect of a phantom limb (Carruthers, 2008). Considering these online and offline characteristics, similar to the study conducted by Slater et al. (2010) using no VB, full static VB, and full tracked VB, this study used three VB conditions (see Table 1). The way the VB was represented in the VR environment was through the use of avatars. Avatars are humanized representations of the body in VR environments widely used in different applications for human-computer and human-human interactions (Etemad-Sajadi, 2016).

Table 1

Virtual Setup Characteristics

Setup	Point of view (Perspective)	Type of virtual body (VB)	Characteristics
1	1st Person	Complete body avatar	First-person point-of-view perspective in which the full body is visible in the HMD.
2	1st Person	Only hands avatar	First-person point-of-view perspective in which only the hands or controls are visible in the HMD.
3	3rd Person (GTA)	Complete body avatar	Third-person point-of-view perspective used in action video games for active body movements. The complete body is observable as an outsider in the HMD.

Note. GTA = Grand Theft Auto; HMD = head-mounted display.

The first simulation was a first-person perspective, with a VB. In this scenario, participants were actively engaged in the activities they performed and saw a VB represented by an avatar that moved according to their movements. The second simulation was again a first-person perspective in which participants were actively engaged, but there was no representation of their bodies. This setup is typical for scenarios in which users way-find inside the virtual environment, but they have only the presence of their virtual hands in that environment. An example of this setup is that used by Google Cardboard, in which participants can realize virtual tours of virtual spaces (Brown & Green, 2016). The third simulation set up was a third-person perspective whereby the participants were able to see their avatar through an outside-body experience. This type of setup is commonly used for action movements in video games such as Grand Theft Auto (GTA) in which the players manipulate the avatars as if they were outside viewers of the physical interactions (Salamin et al., 2006). Likewise, the first and second setups are most commonly used for fine motor skills (Salamin et al., 2006). It is of relevance for this study to acknowledge that both the first- and third-person points of view permit the illusion of body ownership (Galvan Debarba et al., 2017).

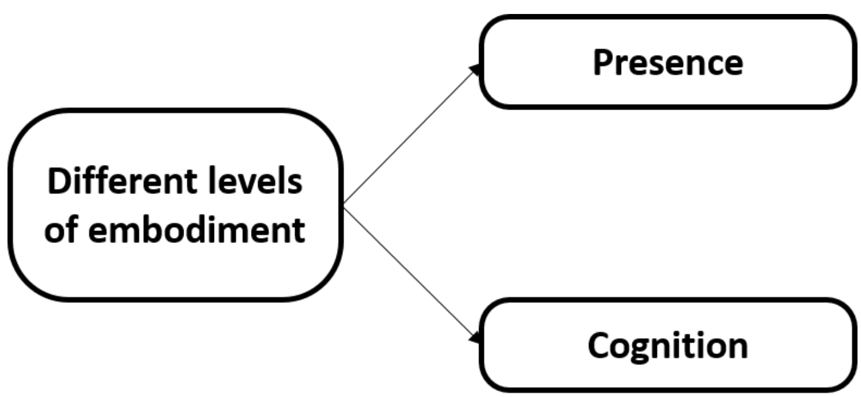
These three setups were selected to support the idea that different variations may positively affect the sense of presence in the virtual environment and liberate cognitive load (CL) in the performed activity. *Presence* was defined by Minsky (1980) as the sensation of “being there” in a different space through the use of technology. For Slater and Wilbur (1997), presence is critical in virtual environments because the higher the sense of presence that participants have, the more likely they are to behave as in real life. For them, presence is a state of consciousness occurring in both subjective and objective manners, understood as the way participants feel in the virtual environment and the way they behave, respectively (Slater & Wilbur, 1997).

Also, previous research suggests how these three setups may affect cognition. For Wilson (2002), cognition is situated and time-pressured, whereby there is off-load of cognitive work in the environment and the environment is part of the cognitive system. Cognition is also about action, and offline cognition is body based. Expanding on Wilson’s (2002) study, cognition is indeed situated because it depends on the environment and the actions developed in that environment (Henning, 2004). Cognition is time-pressured since in a given activity (e.g., driving a car), decisions must be made in a specific time window (Wilson, 2002). Cognitive Load (CL) can be off-loaded in the environment using *epistemic actions*, which are physical actions that liberate CL in the environment (Kirsh & Maglio, 1994). Such is the case of the game Tetris, in which the players manipulate the pieces without thinking about the manipulations, just to see which position best suits the required space. The environment is part of the cognitive system, and as such, environmental features can help explain specific events or situations without necessarily defining regularities in the cognitive process (Wilson, 2002). The statement that cognition is about action is relevant, but the action that permits the storage of information for future use is not restricted by the nature of such storage (Anderson, 2003). An excellent example is a piano, which the mind registers as an instrument. Nonetheless, the function of the piano can change according to the conditions. It can be used as a seat, a table, or even wood for fire when cold. Finally, offline cognition is body based and depicts the ability to generate models of concepts or situations on the basis of previous body experiences (DeSutter & Stieff, 2017).

In summary, different levels of embodiment in IVR affect the sense of presence and cognition (see Figure 1).

Figure 1

Effect of Different Levels of Embodiment



Now the question of how digital media tools can positively affect the design process remains. Cross (1990) discussed the importance of traditional media for ideation stages on the design process and how the interaction of the designer with the media's physicality was critical. Through this physical interaction, the designer is able to see new ideas (emergence) and move the creative process forward (Oxman, 2002). Multiple studies have argued that this is not the case with digital media tools, and on the contrary, they seem to be restrictive for ideation purposes (e.g., Bilda & Demirkan, 2003; Kwon et al., 2005; Meniru et al., 2003; Stones & Cassidy, 2007). However, design students see a lack of detail, inefficiency, and less realistic outcomes in traditional media (Ibrahim & Rahimian, 2010; Jonson, 2005), which encourages the use of digital media tools throughout the design process (Shih et al., 2017).

Multiple studies have addressed how digital media tools can positively affect cognition in diverse disciplines. DeSutter and Stieff (2017) proposed three design principles for embodied cognition in VR learning environments for teaching biology. First, there must be congruency between the actions and the intended cognition; second, participants must predict what the outcomes of the actions should be; and third, the learning environment should be novel. To support these principles, a study was carried out by DeSutter and Stieff (2017) that supported how physical interactions using the body in VR environments enhanced spatial cognitive capabilities of participants. Similarly, Ahn et al. (2014), with two experiments, supported that activities in VR are more engaging and generate learning outcomes that last a longer time. Poulsen and Thøgersen (2011) supported how embodied actions are critical in the design process to generate new ideas.

More specifically in the design discipline, Chandrasekera and Yoon (2015) assessed how three different teaching setups (traditional instruction, VR instruction, and augmented reality [AR] instruction) affected cognition of orthographic projections for design students. In their study, they were able to support that an increase of presence in

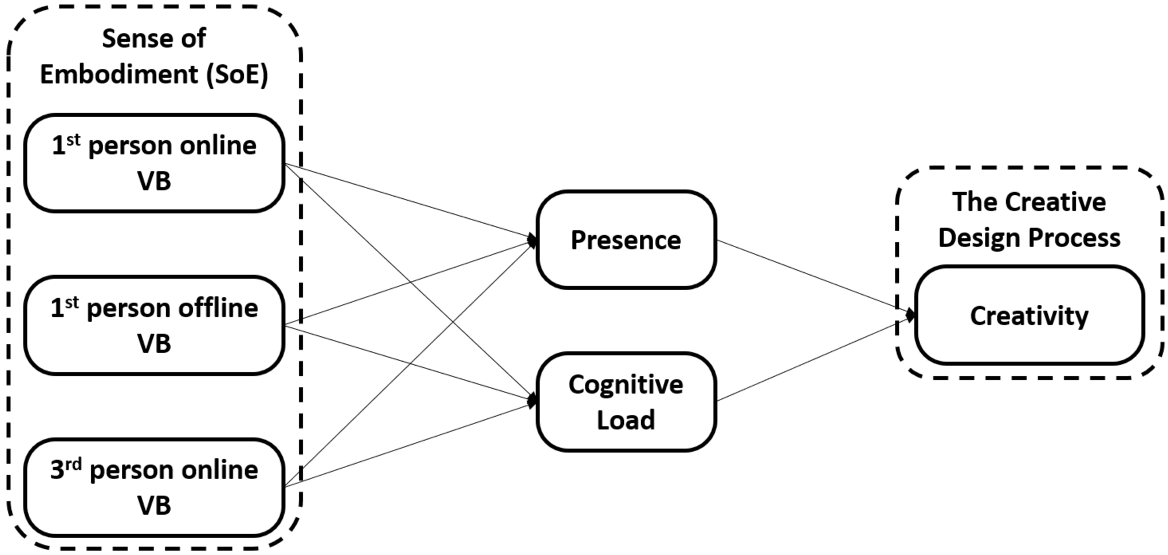
VR environments positively affected spatial rotation abilities. Moreover, Chandrasekera and Yoon (2015) discussed the possibility of diminishing CL in the environment using digital media tools. This decrease in CL is supported by the preference of epistemic actions over pragmatic actions (Kirsh & Maglio, 1994). *Epistemic actions* are physical interactions with the object in hand focused primarily on trial and error, but without deliberate thought, similar to playing Tetris on a computer. The study by Sun and Yao (2012) suggested that there is a relationship between CL and creativity in the design process. They argued that different levels of expertise may also influence this relationship and suggested future research using physiological tools. Rietzschel et al. (2014) discussed how structured approaches to problem solving could reduce the CL and therefore enhance creativity. Finally, the study by Johnson-Glenberg (2018) supported that environments with direct manipulation generate higher learning outcomes. It also suggested that VR is an excellent option when spatial knowledge is required, real impossible features are used for learning, motivation is critical for engagement, and learning skills are transferable to the real world.

Presence is an important factor to elicit creativity in individual processes as well as group collaborations (Heldal et al., 2007). More specifically, Heldal et al. (2007) deemed presence as a critical factor for interactions in VR environments. Similarly, multiple studies have analyzed the way in which being present inside VR environments can affect creativity. Thornhill-Miller and Dupont (2016) discussed how VR through its immersion characteristics enhances creativity and innovation, although they mentioned these tools are currently undervalued. Yang et al. (2018) used electroencephalography to evaluate the difference in creativity between IVR environments and traditional pencil-and-paper ideation sessions. Their findings suggest that VR generated more focused creative activities and enhanced creative outcomes. With a scope of researching the relationship between presence and empathy, Gerry (2017) used VR in creative activities, specifically painting, to engage participants through presence with creative action and showed that VR is a suitable environment to elicit creativity.

As an example of digital media tools, VR provides an embodied engaging environment that helps cognitive processes. This study hypothesized that those more embodied environments, which increase the sense of presence and diminish CL, ultimately affected creativity within the idea-generation stages of the design process (see E). Therefore, the primary focus of this study was to understand how different representations of the VB in IVR environments affect idea generation. As this study focused on how IVR environments affected design education, assessing spatial abilities was appropriate.

Figure 2

Effect of Embodied Environments in the Design Process



Note. vb = Virtual Body.

Purpose of the Study

The purpose of this study was to evaluate the use of high embodiment digital tools, more specifically IVR, as a positive influencer for idea generation and spatial ability development. The main hypothesis was that different VBs affected the SoE, positively increasing presence and reducing CL while increasing spatial ability and creativity. Previous research has suggested that highly embodied digital tools can liberate CL and enhance cognition. The study conducted by DeSutter and Stieff (2017) used *embodied actions*, understood as purposeful movements, which improved cognitive processes in biology students. Furthermore, the study conducted by Chandrasekera and Yoon (2015) reinforced the concept of transparency as a critical factor to enhance the sensation of presence in the digital environment, thereby liberating CL in the participants.

This study formulated the following research question as a key guideline: Do IVR environments with different levels of embodiment enhance creativity?

Research Contribution and Significance

This study explored how creativity of the outcome and spatial abilities were affected by three different levels of VB in IVR environments. This study supported that differently embodied interactions in VR affected spatial abilities. Moreover, spatial abilities increased in participants through the overall interaction in VR environments. This finding has important applications in design education wherein digital media tools are currently thought of as restrictive in terms of the design process but are preferred by design students. It helped to better understand how digital tools can positively affect the design discipline from a design education perspective.

From a technological standpoint, this study helped discern between different applications of the VB in IVR environments. Different VBs have different attributes that can be applied to specific intentions. Previous research has shown how third-person perspective differs from first-person (Salamin et al., 2006), but no research has examined this through the lens of the VB. From a methodological perspective, this study expanded the use of physiological and psychometric tools to analyze the design process.

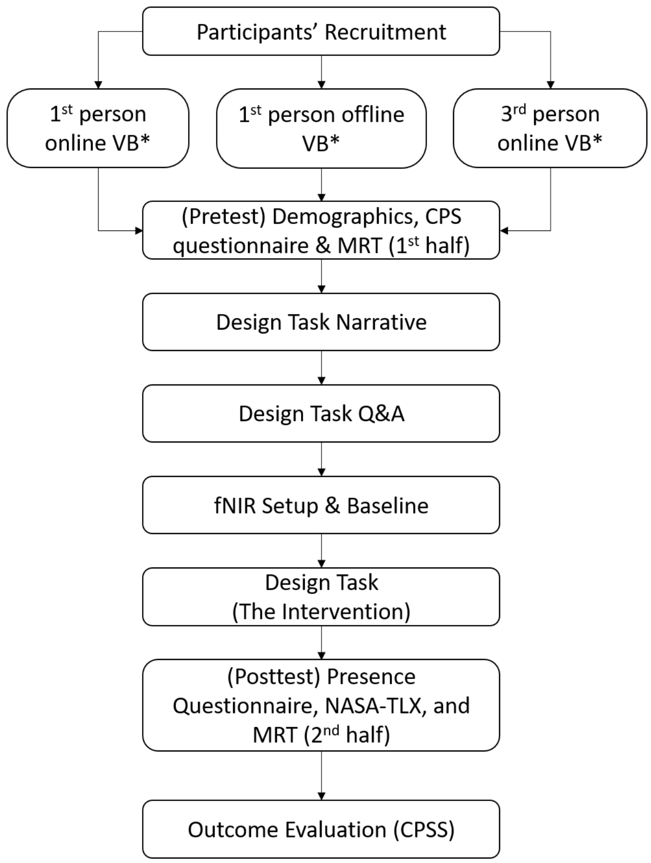
In summary, this study has the potential to positively affect not solely the design education community but also any discipline that uses immersive VR as a medium to enhance cognition and creative thinking.

Research Approach and Methodology

This study used a quasi-experimental approach in which quantitative data was collected pre- and postintervention. A total sample size of 72 undergraduate and graduate students of a midwestern university in the United States were recruited and randomly assigned to one of the three conditions of the VB. The first condition had a first-person point-of-view with VB, the second condition a first-person point-of-view without VB, and the third condition a third-person point-of-view with VB. A self-assessed Creativity Personality Scale (CPS) was administered to all participants before the beginning of the experiment, as well as a Mental Rotation Test (MRT) accounting for spatial skills. Afterward, participants carried out an exercise in an IVR environment using a design brief stating an imaginary futuristic problem. The brief was designed so that the manipulation of objects in the IVR environment was guided by the principles of dominant, subdominant, and subordinate objects to generate a composition (Hannah, 2002). The creativity level of design outcomes was evaluated through the measuring scheme used by Christiaans (2002) that was based on the CPSS. A functional near-infrared spectroscopy (fNIR) device, using light to measure levels of oxygenation in the brain, accounted for a physiological measure of CL. A post-experiment questionnaire assessed the level of presence (Witmer & Singer, 1998), and a NASA–Task Load Index (TLX) survey was used to correlate CL (Wiebe et al., 2010). The second half of the MRT measured any changes in spatial skills (see Figure 3).

Figure 3

Experimental Design



Note. vb = Virtual Body.
MRT = Mental Rotation Test.
CPS = Creative Personality Scale
CPSS = Creative Product semantic Scale

Definition of Terms

Embodiment can be understood from multiple perspectives. From the philosophical point of view, embodiment constitutes how individuals perceive themselves (Wilson, 2002). From the perspective of cognitive neuroscience, embodiment is understood as the way the brain perceives the body and how information from the brain is used to manipulate the body (Dourish, 2001). From the robotics perspective, embodiment is how artificial intelligence (AI) is represented between those creations that exist in the physical world and those that do not. From a more closed perspective, in VR, embodiment is directly correlated to presence (Kilteni et al., 2012).

Sense of Embodiment (SoE) is defined as the "sensations that arise in conjunction with being inside, having and controlling a body" (Kilteni et al., 2012, p. 374). Three elements constitute the SoE: self-location, agency, and body ownership. Location relates to the spatial attributes that an individual has with the environment, agency to the perception of self, and body ownership to the obedience of the body to the mind's intentions.

Virtual Body (VB) is a representation of the individual who is performing tasks in a virtual environment (Slater & Wilbur, 1997). The VB can be divided into online and offline representations of the body where it can be present (totally or partially) or absent, but there is a connection between it and the individual (Carruthers, 2008).

Presence relates to the psychological aspect of the individuals in relation to that technology. Presence is a state of consciousness, which is the sense of being for individuals in the virtual environment (International Society for Presence Research, 2000). Presence can be measured by how individuals feel in the virtual environment and how the individuals behave in the virtual environment through subjective or objective scales. The higher the presence, the more likely the behavior of the individuals mirrors real life.

Cognitive Load (CL) is a concept that refers to the amount of load a given task enforces over the cognitive system; more specifically, the working memory (Paas & Van Merriënboer, 1994b; Sweller, 2010). Cognitive load theory (CLT) comprises three elements: intrinsic cognitive load understood as the complexity of the information processed; extraneous cognitive load related to external presentation characteristics; and finally, germane cognitive load, which is related to the working memory in performing tasks.

Creativity has to do with the ability to produce outcomes that are novel, appropriate, and also have an impact (Palmiero & Srinivasan, 2015; Piffer, 2012). A product can be considered creative only if it is defined as novel, useful, and surprising by expert evaluators Also, *new* is only meaningful in comparison with *old* (Csikszentmihalyi, 1999).

Spatial Ability and *spatial visualization* have been used interchangeably (Yüksel, 2017). Spatial ability is the ability to understand spatial relationships between multiple objects and their surroundings (Nagy-Kondor, 2017; Sutton & Williams, 2007). Thurstone (1938) identified three key factors for spatial ability: *mental rotation*, *spatial visualization,* and *spatial perception*. More recently, Maeda and Yoon (2013) stated that there is no consensus among researchers about the subfactors that compose spatial ability; however, two subfactors are the most common among all the different divisions: *spatial relations* and *spatial visualization* (Burnett & Lane, 1980; Burnett et al., 1979; Hudelot et al., 2008; Kozhevnikov et al., 2007; McGee, 1979; Olkun, 2003; Yüksel, 2017).

CHAPTER II

LITERATURE REVIEW

Emergence in Design

Previous research has found that traditional media tools such as pencil and paper to be a critical factor for idea generation in the design process (Bijl, 1987; Cross, 1982, 1990; Lobell, 1975; Robinson, 2001). Using sketches and models, traditional media tools generate direct physical interaction between the designer's body and their actions and constitute a way in which designers express their thoughts and manage their thinking processes (Cross, 1990; Goldschmidt, 1991). Moreover, the outcomes of these processes are unique because they represent things that still do not exist (Robinson, 2001).

Goldschmidt (1991) supported the importance of these interactions by exposing the relationship between drawings and creativity. Through a series of protocol studies, the researcher explained the design process as a series of operations classified as *moves* and *arguments*. *Moves* were decisions made by designers within the design process, whereas *arguments* were the related statements that originated those moves. These moves and arguments gave origin to two distinctive phases in the idea reinterpretation process that are referred to as *seeing as* and *seeing that.* The iterative loops between these phases were defined by Goldschmidt as a design process dialectic.

For Oxman (2002), *emergence* is a significant outcome of visual reasoning and becomes the key for idea reinterpretation that designers use to understand the world and represent their ideas. For emergence to occur, ambiguity and density are crucial features (Oxman, 2002; Purcell & Gero, 1998). In the words of Oxman (2002, p. 140), "Ambiguity is the condition whereby the syntactic and semantic content of shapes can be legible in diverse ways." Three levels of emergence were defined: *syntactical emergence* in which the designer reads the properties of shapes, *semantical emergence* in which shapes receive a symbolic interpretation, and finally, *cognitive emergence* in which shapes relate to previous knowledge structures, beyond the syntactic and semantic (Oxman, 2002). This last level of emergence is credited to high cognitive actions in the design process (Suwa et al., 1998).

Despite the importance of traditional media for the occurrence of emergence, design students find traditional-media tools such as pencil and paper time-consuming, expensive, lacking in detail, and less efficient to achieve realistic results (Ibrahim & Rahimian, 2010; Jonson, 2005). In contrast, digital-media tools are emerging as a new practice that design students are using throughout the design process (Shih et al., 2017).

How digital tools affect the design process has been studied through multiple lenses. The study conducted by Shih et al. (2015) used protocol analysis to research cognition when using or not using digital media from the beginning of the design process.

They developed two different scenarios. One was sequential mixed media wherein the initial idea of the design process was drafted in analog media, such as sketching with pen and paper, and later moved toward digital media for design development and detail. The other scenario was alternative mixed media, in which designers constantly iterated between analog and digital media without a predetermined sequence along the design process. They concluded that mixed-media environments stimulated creativity by switching between analog and digital tools. Such actions forced the designer to rethink ideas, thus improving design quality (Shih et al., 2017). Wang et al. (2015) conducted a study in which they found that VR encouraged active experimentation. Hence, it affected the way design students learn. For them, VR had a positive influence in the classroom and thus should be encouraged. In this longitudinal study, they found that not because students are introduced to such technology, they would be biased in their learning preference or design strategies (Wang et al., 2015).

VR is widely used in learning and education environments in different disciplines, such as medical teaching applications, engineering training, and design education. One of the main benefits of VR is its capability to emulate existing environments or explore imaginary ones. These VR environments can range from hyper realistic scenarios that mimic interactions in the real world to virtual spaces that can transcend the fundamentals of physics by permitting users to fly, challenge gravity, teleport themselves, and so forth (Kalay, 2004). This ample variety of possibilities in VR has catapulted it into the entertainment industry. Nonetheless, these attributes of variety and control make VR an excellent platform to perform research in the realm of behavioral sciences.

A conventional categorization of VR is between non-immersive and immersive experiences (Mizell et al., 2002; G. G. Robertson et al., 1993). *Non-immersive experiences* are those in which individuals have access to a virtual world through a computer screen and mouse manipulation. On the contrary, *immersive experiences* require special hardware devices, such as head-mounted displays (HMD) that generate stereoscopic vision permitting full-immersion experiences. For Coomans and Timmermans (1997), the main advantages of immersive VR are *visualization* and *natural interaction*. Visualization focuses on the way the information is displayed to users to permit the liberation of cognitive demand through other senses besides linguistic power. Similarly, natural interaction allows a more accessible interface between the human and the computer through more intuitive devices than a mouse. An excellent example of these advantages was the study conducted by Steed et al. (2016), which found that through avatar visualization and body movements, participants were able to increase cognition in immersive VR environments.

From Cognition to Embodiment

Embodiment and cognition are two concepts that relate to each other. The way individuals interact with the world to generate understanding of it has been widely discussed in the past, starting with Descartes's notion that mind and body are distinct (Kenny, 1985). This separation of body and mind is understood by the cognitivist approach in which the manipulation of symbols—which generate meaning—under explicit rules can account for the central functions of the mind (Clark, 1998). Descartes acknowledged a difference between body and soul from an ontological perspective, but he also understood that they formed an empirical unity (Anderson, 2003). Furthermore, although Descartes thought of the mind and body as separate entities, he realized that the way the mind acquired knowledge was by the mediation of the senses; hence, the body within Cartesian philosophy was instead a conundrum between the notion of being necessary to acquire knowledge yet independent from the mind.

According to Taylor (1995, Chapter 1), it was Heidegger who helped advance the discussion between mind and body. For Heidegger, individuals are agents in the world that are meant to be *coped* with the physical context which surrounds them. Even if individuals want to formulate thoughts on the basis of the pure mind, they must relate with the world, experiment with it, or even observe it. The only way to perform such deeds is by interacting with the world throughout their bodies. In a similar argument, Merleau-Ponty emphasized the importance of context as a starting point for perception and representation. That context becomes a critical factor by which individuals can reflect and interact with the existing world only through direct bodily engagement (Hilditch, 1997).

Asking someone for directions to reach a certain place is a practical way to illustrate the connection between mind and body. To respond, the first step the individual will most probably consider is to visualize being in a given context. The study conducted by Franklin and Tversky (1990) explored what they defined as *the spatial framework hypothesis* in which the perception and interpretation of the surrounding context was directly related to the individual's body position. Moving forward with this example, once the individual realizes where they are, they must picture the destination. This will enforce a possible route to explain, which the individual will have to travel in thought only, imagining all the moves and turns as well as any given obstacle that may be encountered along the way. Such a reflection of movement in space forges a deep relationship between the individual's mind and body as a means of thought generation. Finally, the individual will have to communicate these reflections to the person asking for directions. Chu and Kita (2011) were able to show how gestures positively affected the perception of spatial problems between individuals who gestured and their non-gesturing counterparts. Most frequently, in the "giving directions" example, the individual will gesture to communicate the selected route.

Besides the previous practical example to illustrate the connection between mind and body and also the relevance of embodiment and cognition, there are multiple empirical studies that support such connection. From the design discipline's perspective, the study by Poulsen and Thøgersen (2011) used Buur's model of focus, reflect, and reframe for conversation analysis to research embodiment as a critical factor for problem analysis and idea generation in the design process. The main finding of this study was that design thinking cannot rely solely on verbalization. Framing the problem and generating ideas requires multidimensional interactions that are based on the use of the whole body. Similarly, the study by Chandrasekera and Yoon (2015) displayed an increase in mental rotation ability by the use of multiple instructional modalities, which varied in level of embodiment. Within the field of science, technology, engineering, and mathematics (STEM), DeSutter and Stieff (2017) studied embodied actions, using them to appraise cognition of molecular structures in biology students. In conclusion, the use of the body in cognition is an increasing field of research, and as Maya Lin (2016) stated in her book *Boundaries*, "I think with my hands" (3:09).

Embodiment

The previous paragraphs explained the importance of cognition and its relationship to the concept of embodiment. Dourish stated, “Embodiment is the property of our engagement with the world that allows us to make it meaningful” (2001, p. 126). This definition includes not only the relationship between the individual and the real world but also the world used as a metaphor. To clarify this concept, an example could be a 3-D digital environment in which the interaction between the individual and the environment is attained by the use of common rules established in the real world. Nonetheless, a virtual environment is not a real world but rather a metaphor for an existing one. Alibali and Nathan (2012) stated that although no unified theory on embodiment exists, embodiment relates to body-based systems, which include the physical and neural dimensions. Wilson (2002) said that embodiment is a brain-based phenomenon in which the world is represented by the brain running simulations of the physical world.

Embodiment involves not only explicit interactions with the world but also implicit ones. Winograd and Flores (1986) explored their theories in computational cognition by using the concepts of *ready-to-hand* and *present-at-hand* proposed by Heidegger. An excellent example to understand these two concepts is the use of a computer mouse, which is intended to provide interaction with the computer. When an individual moves the pointer on screen, they focus on it (moving around, scrolling, or clicking at buttons) rather than on the physical mouse. At this point, the mouse is *ready-to-hand*. In contrast, if by chance, the mouse moves away from the mouse pad, and the individual must relocate the mouse, the concept of *present-at-hand* takes place.

Furthermore, studies have explored the relationship between explicit and implicit interactions from different perspectives. L. L. Chao and Martin (2000) found that visualizing objects that involved physical action activated parts of the brain that were related to the actual physical action. This finding suggests that acknowledged objects used in the past generate imagined interactions. Similarly, Ganis and Thompson (2004) presented participants with a visual image as a stimulus, which later was reimagined without the presence of it, yielding the same brain activations as when the stimulus was present. These examples further deepen the concept of embodiment and its relation to body, mind, and environment.

From Embodiment to Sense of Embodiment

According to Anderson (2003), it is possible to identify four aspects that play a critical role in embodiment. These aspects are physiology, evolutionary history, practical activity, and sociocultural situatedness. *Physiology* is understood as the physiological constraint of the body to relate to the perceived world. An example of this could be the perception of visible light, which is controlled by the physiological aspects of the human eye. Infrared light and ultraviolet light are components of white light, but the human eye is not able to register these frequencies due to physiological limitations. The second aspect is evolutionary history. Given that embodiment relates to the mind and body (Taylor, 1995, Chapter 1), this aspect can be explained by each. From the body's perspective, a good example of human evolution can be the lack of fur replaced by the use of clothing. On the other hand, relating to mind, an example is the way humans code and decode social messages over time. Oxman (2002) talked about *emergence* as a significant outcome of visual reasoning that becomes key for idea reinterpretation, and this visual reasoning relies on codes and symbols related to specific time or period. The third aspect of embodiment is a practical activity that relates directly to the way humans interact with the world. An example of this aspect is *epistemic actions,* defined by Kirsh and Maglio (1994) as actions that involve physical manipulation of the problem looking for a solution, such as disassembling a component and orderly arranging the pieces to later ease the assembly process. Finally, there is the sociocultural situatedness aspect, which refers to the cultural and social contexts behind the meaning. An altar, for example, is a flat tablelike surface; however, the interaction with an altar and the meaning behind it will not be as if it were a table.

Similarly, Dreyfus (1996) built upon the work of Merleau-Ponty and discussed three levels of embodiment: physical, body skills, and cultural skills. The first level comprises physical elements (hands, legs, etc.) that engage and interact directly with the physical world. The second level refers to developed body skills and situational responses or interactions. Finally, the social and cultural world in which each individual is embedded constitutes the third level. Likewise, T. Robertson (1997) introduced two concepts, the first being the concept of *reversibility*, understood as the dialogue of embodiment between the individual who performs it and the observer who responds to it, and vice versa. This concept may relate directly to the cultural level of embodiment proposed by Dreyfus. The second concept was the manifestation of embodiment through *embodied actions*, the "actions of an active and perceiving subject" (T. Robertson, 1997, p. 209), which relate to the body skills level. Through the research of embodied actions, DeSutter and Stieff (2017) introduced the relevance of *purposiveness*. They argued that every action is not an embodied action, and for it to be called so, the action should be purposeful and intentional.

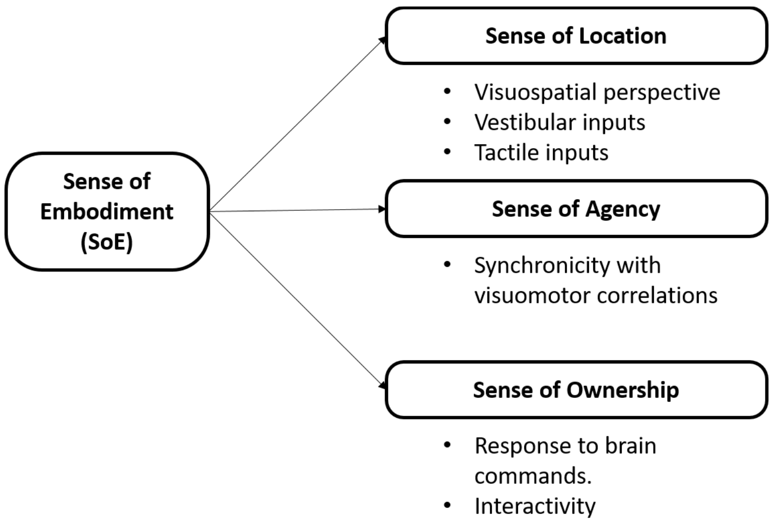
The work of DeSutter and Stieff (2017) not only highlighted the importance of purposiveness in understanding embodiment but also proposed three principles to consider when designing interventions. The first principle is the inclusion of *scaffold*, which explicitly relates the activity with the bodily movements. A *scaffold* is explained by Anderson (2003) with the definition used in cognitive sciences: It occurs when an epistemic action constitutes a cognitive aid. Moreover, the first principle of *scaffold* relates to *congruency*, understood as the relationship between the intention of the action and its outcome (e.g., when riding a bicycle, the individual wants to go left; he must steer to the left). The second principle is that embodiment should stimulate operations that can be imagined by the individual. This second principle talks about prediction (e.g., when an individual releases an object in midair, the object should drop down by the effect of gravity unless there are different variables in play). Finally, the third principle discusses the innovation aspects of the environment to perform the embodied actions. Stimulating environments that portray innovative visualization techniques or object manipulation will stimulate new interactions within the individual and the environment (DeSutter & Stieff, 2017).

The relevance of embodied actions within the concept of embodiment is enhanced by Kilteni et al. (2012) when they discuss the SoE. In their words, “Sense of embodiment will be used to refer to the ensemble of sensations that arise in conjunction with being inside, having and controlling a body” (p. 374). More specifically, SoE comprises three subcomponents: the sense of self-location, the sense of agency, and the sense of body ownership (Carruthers, 2013; Kilteni et al., 2012; Slater et al., 2010). The sense of self-location contains the spatial attributes that an individual has with the environment. The sense of agency relates to the perception of self and body ownership to the obedience of the body to the mind's intentions. Finally, the sense of body ownership refers to the compliance of the body to the mind's intentions (Kilteni et al., 2012).

Self-location comprises the visual-spatial perspective between the individuals and the environment, the vestibular inputs that individual receives, and the tactile inputs by which that individual can interact with the environment. *Agency* depends mainly on the synchronicity of the visuomotor relationship between the individual and the environment. Finally, the sense of body ownership comprises two distinct flows, bottom-up and top-down; the former is understood as the transmission of experiences from the senses to the brain, and the latter, as the messages from the brain to the body parts (Kilteni et al., 2012). Similarly, these three concepts may be found in the realm of presence research in virtual environments (Lee, 2004; Lombard & Jones, 2015b; see Figure 4).

Figure 4

Sense of Embodiment



Sense of Embodiment in Context

Theoretical foundations of embodiment evidence the connection between body and mind and the relevance of both in cognition. Embodiment is a strategy to generate meaning of the surrounding world on the basis of the foundations of ontology, intersubjectivity, and intentionality (Dourish, 2001). Embodiment not only improves cognitive processes (DeSutter & Stieff, 2017) but also emphasizes the awareness of the individual in the role as the main character performing a given activity (Anderson, 2003). Accordingly, embodiment is not only a way an individual interprets and understands the world on the basis of their own beliefs but also how peers understand that individual. Furthermore, embodiment helps bridge the gap between awareness of knowledge and reality. This bridge is the concept of ready-to-hand and present-at-hand as portrayed by

Winograd and Flores (1986) or the concept of coping, which refers to the interaction between individual and artifact (Anderson, 2003; Dourish, 2001).

In the current study, three different levels of SoE were assessed. More specifically, with the understanding that the VB is a self-recognition of a given subject within a virtual environment (Slater et al., 2010), SoE can be researched. In a similar manner as the study conducted by Slater et al. (2010), three different levels of the VB were evaluated to measure their impact on presence and cognitive load, ultimately affecting spatial skills and idea generation. In accordance with Lee (2004) and his description of self-presence in virtual environments, two of the levels were in the physical realm (using a complete avatar in first and third person), and a third level was in the psychological realm using first-person view without a body.

Presence

According to Lombard et al. (2015), the concept of *presence* was first used in the early 1950s by the film theorist André Bazin in a scholarly context. Bazin discussed the relationship that emerged between the viewer and the actor as well as how the screen between them worked as a mirror that reflected the presence of the person portrayed in it. Similarly, the concept of *co-presence* was presented by Erving Goffman in his book *The Presentation of Self in Everyday Life*, first published in 1959. For Goffman (1959/2002), when two individuals are located side by side, each is able to perceive what the other is doing. It was only when Short et al. (1976) researched the impact of the mediation of media and its relationship with social interactions that technology became the focus of attention within the research on presence. Since then, much has been debated about the concept, and multiple definitions have arisen.

In his article "Presence, Explicated," Lee (2004) expands three of the most common types of presence: *telepresence, virtual presence*, and *mediated presence*. *Telepresence* was presented by Minsky in 1980 and has become the most used variant of the concept nowadays, according to Lombard et al. (2015). Minsky stated:

> Each motion of your arm, hand, and fingers is reproduced at another place by mobile, mechanical hands. Light, dexterous and strong, these hands have their own sensors through which you see and feel what is happening. Using this instrument, you can "work" in another room, in another city, in another country, or on another planet. . . The biggest challenge to developing telepresence is achieving that sense of "being there." (1980, p. 45)

For Minsky (1980), *telepresence* was the possibility for an individual to transport through technology to a different space. He saw the future of telepresence as a way to fulfill dangerous jobs, reduce transportation costs, develop new surgical procedures, or even improve working conditions by permitting individuals to work remotely. Similarly, multiple researchers have defined *telepresence* as the feeling to actually be there, an out-of-body experience, being in a different location without being physically there, or even a "suspension of disbelief" in which individuals are in a different world from that in which they have their body (e.g., McLellan, 1996; Rheingold, 1991; Sheridan, 1995; Slater & Usoh, 1993).

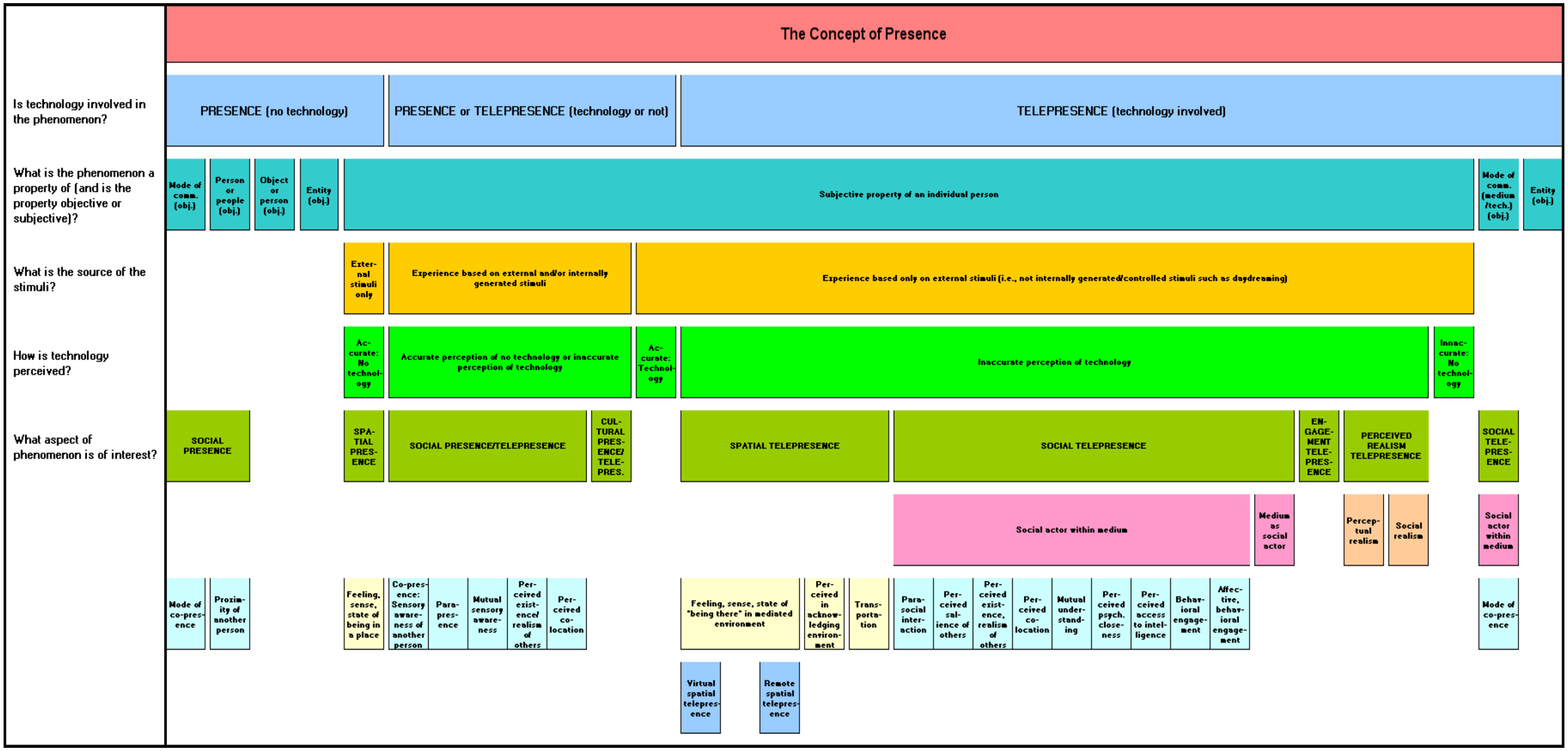
Sheridan (1995) introduced the concept of *virtual presence,* referring specifically to the outcome of presence generated by the application of VR technologies. His main objective with such a definition was to differentiate virtual presence from the concept of telepresence, which related directly to teleoperation systems.

The term *mediated presence* was coined by Biocca et al. (2001), who aimed to differentiate it from the natural perception of an environment. *Non-mediated* or *natural perception* is the concept of presence without the involvement of a mediator between the stimuli and the recipient. Biocca et al. (2001) argued that if such distinction did not exist, the area of presence research would be too broad. Nonetheless, the differentiation between natural and mediated presence seems to be a futile quest. From a practical standpoint, any stimuli that is received in a natural form from the environment, without any technological mediation, will be perceived through the senses and hence mediated somehow (Lee, 2004). This argument is easily understood by the differentiation between sensation and perception. *Sensation* is the response of the senses to physical stimuli, in contrast to *perception*, which involves the interpretation of that stimuli concerning extraneous factors, such as emotion, cognition, and experience (Baron & Byrne, 1987). Congruently, it may be said that the way the natural world is perceived is the same as that of a virtually generated one (Loomis, 1992).

Lombard and Jones (2015b) developed a table that organized most of the different scholarly definitions for *presence* throughout academic publications in diverse disciplines. (see Figure 5). An interactive version of this table can be found online (matthewlombard.com/presence-definitions/).

Figure 5

Defining Presence (Lombard & Jones, 2015a). Framework of Presence Definitions



During the spring of 2000, interdisciplinary scholars participating in an online discussion for the International Society of Presence Research (ISPR) agreed on a comprehensive explanation of the concept.

> Presence (a shortened version of the term "telepresence") is a psychological state or subjective perception in which even though part or all of an individual's current experience is generated by and/or filtered through human-made technology, part or all of the individual's perception fails to accurately acknowledge the role of the technology in the experience. Except in the most extreme cases, the individual can indicate correctly that s/he is using the technology, but at *some level* and to *some degree*, her/his perceptions overlook that knowledge and objects, events, entities, and environments are perceived as if the technology was not involved in the experience. Experience is defined as a person's observation of and/or interaction with objects, entities, and/or events in her/his environment; perception, the result of perceiving, is defined as a meaningful interpretation of experience." (International Society for Presence Research, 2000, para. 4)

The ISPR's definition is the one that will be used in this study, and from this point on, the concept will be referred to as *presence*.

From a theoretical standpoint, presence is composed of a series of dimensions that sometimes overlap. These dimensions are typically categorized as spatial presence, social presence, self-presence, engagement, realism, cultural presence, and parapresence (Lombard & Jones, 2015b). Three of those dimensions are deemed critical for the research of presence in virtual environments (Lee, 2004), and two are crucial from an immersion standpoint (Slater & Wilbur, 1997).

Spatial presence is the most common of the dimensions of presence and relates immediately with the surrounding environment (Lombard & Jones, 2015b). This relationship between the environment and the individual is explained by the sensation of "being there" while remaining physically somewhere else (e.g., Biocca et al., 2003; Lee, 2004; Witmer & Singer, 1998). It is important to bear in mind that this sensation of being there can be either in a virtual non-existing environment, which can be technologically developed, or in an actual existing remote location (Lombard & Jones, 2015b).

Another dimension of presence is defined as social presence. This pertains to the relationship that occurs between social actors, but it is not exclusively applied to humans (Lee, 2004; Lombard & Jones, 2015b). Two examples of this dimension of presence are (a) talking through a telephone by which two individuals are connected and (b) humanizing a living or nonliving object, such as addressing a pet or talking to a computer.

The third dimension of presence is defined as self-presence. Even though the theory of self-presentation is presented by Goffman (1959/2002), this dimension of presence will correspond to the way individuals relate to self-representations of themselves in virtual environments (Lombard & Jones, 2015b). It is important to understand that there are two basic ways in which this dimension is relevant. The first is when the self is represented through technology in a virtual environment, and the second when the self is represented on a remote environment (Lee, 2004).

Engagement is proposed as the fourth dimension of presence (Lombard & Jones, 2015b). In the book *Flow and the Foundations of Positive Psychology*, Csikszentmihalyi et al. (2014) talk about the concept of *flow*. They define *flow* as that capability to perform activities that require considerable effort and do not necessarily yield any outcome besides the satisfaction of doing such activity. This type of behavior will generate a strong connection between the action performed and the individual (Lombard & Jones, 2015b).

The next dimension of presence discusses the condition of realism understood as the correspondence between an environment not mediated by technology and another mediated by it (Slater & Wilbur, 1997). More specifically in virtual environments, Lee (2004) talked about para-authentic and artificial objects. *Para-authentic objects* are those objects that relate to something existing in reality. An example is when an individual visits the Eiffel Tower in a VR setup. This is not the real tower, but a representation of that existing in Paris. In contrast, when an individual interacts with an object that has no equivalent in the real world, it is defined as an *artificial object* (Lee, 2004). It is essential to bear in mind that this differentiation between para-authentic and artificial objects has no relationship whatsoever to the richness of the representation (Milgram & Kishino, 1994). Instead, Lee suggested that the realism of an experience relies on the authenticity of it rather than on the vividness.

Measuring Presence

Considering the framework proposed by Lombard and Jones (2015) to define *presence*, this study makes the following distinctions. First, an IVR environment mediated the interaction. Second, the presence was mediated by differences in self-awareness resulting from diverse VBs in the VR environment. Third, the source of the stimuli was external to the individual. The individual was immersed in a VR environment with a high correlation between *place-illusion* and *plausibility,* as defined by Slater et al. (2010). *Place-illusion* relates directly to the vividness and richness of the interaction (e.g., lighting setup, resolution of the headset), whereas *plausibility* refers to the comparison between the expected and the outcome (e.g., gravity, movement relationship). Fourth, the perception of technology was expected to be of inaccurate perception. This relates to the previously explained concept of ready-to-hand versus present-at-hand (Winograd & Flores, 1986). It was intended a high transparency of technological hardware as a mediator, more specifically, the VR HMD and the controllers. Last, even though dimensions of presence may overlap (Lee, 2004; Lombard & Jones, 2015b), this study focuses on spatial presence, social presence, self-presence, engagement, and realism. To measure presence, multiple self-report questionnaires were used. More specifically, this study relied on the presence questionnaire compendium (Baren & IJsselsteijn, 2004) and the Witmer and Singer (1998) questionnaire.

Cognitive Load

The origins of research on CLT date to the 1980s, with a noticeable development by the following decade (Paas et al., 2003; Sweller, 1994). CLT explores the cognitive architecture of human beings and how it performs in given tasks. When referring to cognitive architecture, the first and most important component is long-term memory (Sweller et al., 1998). *Long-term memory* is where knowledge is located under the form of schemas (Paas et al., 2003; Sweller et al., 1998). A *schema* is a categorization of several information chunks concerning future use. Schemas have multiple levels of complexity. They are crucial for cognition because they not only store information but, through automation, reduce the load over the working memory (Sweller et al., 1998). Working memory constitutes the second component, and according to Miller (1956), it is capable of simultaneously maintaining only around seven chunks of information. Moreover, humans probably can deal with only two or three chunks simultaneously (Sweller et al., 1998). Besides, several interrelated structures and two main systems constitute working memory, one dedicated to processing visuospatial information and the other to process auditory information (Baddeley, 1992).

Cognitive load is a concept that refers to the amount of charge a given task enforces over the cognitive system; more specifically, the working memory (Paas & Van Merriënboer, 1994a; Sweller, 1994, 2010). Mental load and mental effort are two dimensions that comprise cognitive load and ultimately affect performance. The first relates directly to the task, whereas the second relates to the learner (Sweller et al., 1998). Moreover, cognitive load falls into three different classifications. The first type is *intrinsic cognitive load* and refers to the specific complexity of the activity in hand. The second is called *extraneous cognitive load* and relates to external characteristics while performing the task that do not contribute to learning. The last, *germane cognitive load*, refers to the mental activities that directly relate to learning and building schemas (Renkl & Atkinson, 2003; Sweller et al., 1998). The first type relates directly to the task's complexity, but instructional theory suggests that resources can be allocated between extraneous and germane to improve cognition (Sweller et al., 1998).

It is important to remember that these three types of cognitive load are additive and restricted by the capacity of the working memory. If by chance they exceed the capacity of the working memory, it will jeopardize information processing and cognition. Theory suggests that by reducing extraneous cognitive load, resources can be destined to intrinsic and germane cognitive load, which ultimately will increase cognition. An important consideration of this statement is that intrinsic cognitive must be high; otherwise, variations in extraneous load will not be noticeable due to existing working memory capacity (Sweller, 2011). Moreover, Sweller (2011) proposed multiple cognitive load effects that generate variations in the contribution of the three cognitive load types. Intentionally using these cognitive load effects can improve cognition.

Digital tools such as VR can help to reduce cognitive load. The study conducted by Yu et al. (2015) showed that these type of tools, through manipulation, show evidence of the occurrence of *design patterns*. These are core solutions to problems that can be repeated over and over again, always generating different outcomes. Also, digital mediums permit the manifestation of *epistemic actions*, as defined by Kirsh and Maglio (1994). These actions free cognitive load through physical manipulation of the problem while an individual looks for a solution, in contrast to pragmatic actions that imply thinking on the solution before the manipulation process. In her work, Wilson (2002) mentioned the important relationship between body and environment for cognition. More specifically, she discussed how, through body actions, individuals are capable of releasing cognitive load into the environment, permitting an increase in cognitive processes. In doing so, individuals rely on preloaded representations (design patterns) acquired through previous learning and epistemic actions (Wilson, 2002). Through the use of VR environments that strengthen the relationship between body and environment, the present study hypothesized that it would liberate cognitive load, ultimately increasing cognition.

Measuring Cognitive Load

This study considered four cognitive load effects when designing the intervention for the participants: *completion, split-attention, guidance fading,* and *imagination* (Sweller, 2011). The study conducted by Paas and Van Merriënboer (1994a,1994b) concluded that partially resolved problems might have the same effectiveness as worked examples, addressing the *completion* effect. The *split attention* effect represented by the increase in cognitive demand as an outcome of receiving information in multiple formats was discussed by Ayres and Sweller (2005). They concluded that integrated formats would enhance cognition. Slijepcevic (2013) suggested that mixed reality interfaces reduce cognitive load by integrating multiple information in one view. The study by Steed et al. (2016) supported the notion that the avatars in VR help cognitive processes. More interesting, their study involved body movements and concluded that those participants who were physically active had better cognition on the required task. The importance of *fading guidance* was addressed by Renkl (2005) when he discussed expertise growth and how problems must gradually replace examples. Finally, Leahy and Sweller (2004) discussed the importance of *imagination* in contrast to studying materials. Through imagination, individuals imagine new tasks in combination with previously learned processes in their working memory. The relevance of these findings supported that the combination of the previous and the new permits an increase in cognition.

Psychometric tools, as well as physiologic tools, are commonly used to assess cognitive load (Wierwille & Eggemeier, 1993). From the psychometric perspective, one of the more frequently used tools to measure cognitive load is the NASA-TLX questionnaire. This questionnaire uses a Likert scale that measures cognitive demand in six different aspects of task performance (Hart & Staveland, 1988). More important, its reliability has been evaluated over time, strengthening its acceptance as a testing method (Hart, 2006; Hoonakker et al., 2011; Xiao et al., 2005). From a physiological perspective, measuring cognitive tasks in the brain can be achieved by the use of neuroimaging tools such as functional magnetic resonance imaging (fMRI), which can monitor neural activity.

fNIR devices are a more flexible and less expensive research method into brain activity and cognitive tasks (Ferrari & Quaresima, 2012). Furthermore, these permit researchers to register brain activity while physical tasks are being performed in natural environments (Kaimal et al., 2017). To be portable and noninvasive, fNIR uses light to measure oxygenation and deoxygenation levels in the blood to quantify brain activity (Ayaz et al., 2013). Major levels of oxygenation demand in the blood correlate to higher brain activity, hence major cognitive load (Ayaz et al., 2013; Kaimal et al., 2017). Moreover, the study conducted by Szulewski et al. (2017) was able to correlate the relationship between psychometric and physiologic tools as empirical indicators for the cognitive load.

The study by Bric et al. (2014), using the NASA-TLX as a tool to assess cognitive load, explored the impact of VR as an instructional environment for surgeons. Similarly, Pouliquen-Lardy et al. (2016) used VR and the NASA-TLX to measure remote collaboration, task distribution, and spatial processing. Moreover, the study by C. J. Chao et al. (2017) contrasted VR and traditional training methods over training performance and mental workload. Their main finding was that VR was a better training method concerning task complexity and task performance.

Defining *Creativity*

The term *creativity* has been widely used in the context of design and design instruction, yet it seems to be vague and has multiple interpretations. Torrance (1988, p. 43) stated, "Creativity defies precise definition." Other researchers and scholars have proposed multiple definitions. Rhodes (1961) defined *creativity* as a combination of four distinct categories, better known as the four P's of creativity (person, process, place, and product). He discussed that creativity was a mixture between the individual aspects of who is involved in the creative process (person), the cognitive aspect of the creative action (process), the direct influence of the context where the action is taking place (place), and finally, the creative outcome or product resulting from the creative process (product). Furthermore, Rosenman and Gero (1993) discussed that creativity could be narrowed in terms of product and process. Creativity in the product refers to when the outcome exhibits properties of innovativeness, has new definitions of value, or allows new interpretations. In contrast, creativity in the process relates to when that process has the capability of yielding creative products (Rosenman & Gero, 1993).

Similarly, Csikszentmihalyi (1999) argues that creativity does not rely on the mind of the individual doing creative thinking but in the viewer's perception of the outcome. In addition, he stated that the new is only meaningful in comparison with the old. Creativity is the ability to solve problems that generate novel and useful solutions (Runco, 2008). For Piffer (2012), creativity is the number of creative products that any certain individual attains overall. Despite the multiple definitions, creativity speaks about the ability to produce outcomes that are novel, appropriate, and have an impact (Palmiero & Srinivasan, 2015; Piffer, 2012).

Furthermore, the discussion about creativity being domain-general or domain-specific has been going on for some time (Baer, 2010). *Domain-general* comprises skill-sets that yield creative outcomes in any domain, regardless of the field of expertise; on the contrary, *domain-specific* outlines traits and skills that are pertinent to domain characteristics. Guilford (1950; Guilford & Hoepfner, 1971) proposed a model in which the multiple areas that compose creativity (visual, auditory, symbolic, semantic, and behavioral) are used in diverse domains to yield novel outcomes. Moreover, Kaufman et al. (2009) defined seven more specific areas in which creativity manifests itself (entrepreneur, performance, math/science, problem solving, artistic/verbal, interpersonal, and artistic/visual). Feist (2004) discussed how creativity is similar to intelligence and the degree to which it is possessed or not from a domain-general standpoint. He further debated how creativity is composed of specific heuristics and mental strategies that are in the domain-specific realm. From a domain-specific perspective, design education deems creativity and spatial abilities of crucial importance (Allen, 2010; Cho, 2017; Zacks et al., 2000).

Moreover, to define creativity, it is important to discern between the distinctions of the "little-c" and the "big-C" of creativity. For Csikszentmihalyi (1998) the little-c better relates to a personal creativity, whereas the big-C goes more in line with his thought that creativity must be culturally accepted and appropriated. Kaufman and Beghetto (2009) refer to the big-C as those genius-type creative outcomes of eminent greatness, in contrast to the little-c, which refers to everyday common creativity that can be found across humankind. Given these distinctions, it was the interest of this study to focus on those little-c's, understood not as that giant leap in innovation, but rather as those small steps, or *a-ha* moments, that previous research has deemed as critical to move the design process forward (e.g., Cross, 1990; Goldschmidt, 1991; Robinson, 2001).

Creativity and Spatial Abilities

Thurstone (1938) suggested that a specific intelligence is the outcome of a combination of mental abilities. These mental abilities include associative memory, perceptual speed, number facility, spatial visualization, reasoning, word fluency, and verbal comprehension. Gardner (1983) proposed the framework of multiple intelligences theory, which supports the relevance of spatial ability in design education. Eight types of intelligence constitute Gardner's model: logical mathematical, linguistic, musical-rhythmic, bodily-kinesthetic, visual-spatial, interpersonal, intrapersonal, and naturalistic. Nonetheless, in this model, individuals mainly focus on one type of intelligence. However, D'Souza (2006) claims that design intelligence is instead a holistic intelligence that must combine different elements of existing intelligences. He compares designers with decathlon athletes who must train in one specialty but nonetheless compete in multiple events (D'Souza, 2006). Also, more than referring to intelligences, D'Souza talks about abilities or skills.

The terms *spatial visualization* and *spatial ability* have been used interchangeably (Yüksel, 2017). Multiple authors have defined *spatial ability* in diverse ways. Lohman defined it as "the ability to generate, retain, retrieve, and transform well-structured visual images" (1996, p. 3). Earlier, McGee defined spatial ability as "the ability to mentally rotate, manipulate, and twist two- and three-dimensional stimulus objects" (1979, p. 909).

Mayer and Sims (1994) defined *spatial ability* as the capacity to visualize a 2-D or 3-D object after it has changed, rotated, or moved in space. A similar definition is that spatial ability relates to the performance of a task that involves mental rotation of objects in space, understanding of how objects will be perceived from different angles, and the relationship between objects in space (Sutton & Williams, 2007). Overall, the consensus is that spatial ability refers to a developed skill to connect the perceived and the physical tridimensional world (Nagy-Kondor, 2017).

Over the years of research, multiple subfactors have been proposed to understand spatial ability (Yüksel, 2017). Initially, Thurstone (1938) identified three key factors in spatial ability: *mental rotation*, *spatial visualization,* and *spatial perception*. More recently, Maeda and Yoon (2013) stated that there is no consensus among researchers about the subfactors that compose spatial ability; however, two subfactors are the most common among all the different divisions: *spatial relations* and *spatial visualization* (Burnett & Lane, 1980; Burnett et al., 1979; Hudelot et al., 2008; Kozhevnikov et al., 2007; McGee, 1979; Olkun, 2003; Yüksel, 2017). These two subfactors correlate in practice, although they are theoretically independent (Maeda & Yoon, 2013). The first relates directly to imagining rotations of 2-D and 3-D objects as a whole body, whereas the second refers to the ability to imagine the rotations of 3-D objects as well as the objects' construction or deconstruction. Nonetheless, Olkun (2003) claims that this separation is artificial because both components can be juxtaposed one over the other. In fact, the subtle differences between these two are explained by two continuums: speed–power and simplicity–complexity, in which spatial relation is located at the left of the range and spatial visualization at the right (Pellegrino et al., 1984). Spatial visualization is of interest for this study due to its high power and high complexity.

Spatial abilities research has used multiple tests to measure different aspects (Sjölinder, 1998). A measurable indicator of spatial visualization is mental rotation, and it entails the rotation of an object (2-D or 3-D) as a result of a cognitive process (Carroll, 1993, as cited in Maeda & Yoon, 2013). Also, mental rotation tasks are a clear example of the ability of individuals to mentally manipulate objects (Shepard & Metzler, 1971) and have been widely applied in spatial abilities research (Peters & Battista, 2008). Another key indicator is spatial orientation, understood as the capacity to engage with the environment using the perspective of the individual as a reference point. Multiple studies have analyzed the capabilities of VR to assess spatial orientation (Darken et al., 1998; Keshner & Kenyon, 2009). In their study, Keshner and Kenyon (2009) concluded that VR environments are suited for emulating real-world experiences in terms of spatial orientation from a clinical standpoint. Also, the study of Allahyar and Hunt (2003) provided a set of benefits and disadvantages of using VR for spatial orientation research. They concluded that with the proper settings, VR could permit good experimental setups for spatial ability research.

Spatial ability has a very important role in STEM instruction and development. In addition, multiple studies have acknowledged the relationship between spatial skills and performance (Uttal & Cohen, 2012). Because of this, spatial ability has driven special attention to researchers in the STEM fields. Relationships have been drawn between spatial ability and anatomy (Vorstenbosch et al., 2013), math (Bosnyak & Nagy-Kondor, 2008), engineering education (Alias et al., 2002), and more specifically, design education (Lin, 2016).

Besides, spatial ability relies on motor skills, and as such, it can be affected by neural plasticity. *Plasticity* refers to the changes occurring in short periods of time in the brain, more specifically in gray and white matter associated with motor skills (Dayan & Cohen, 2011). The study by Subrahmanyam and Greenfield (1994) supported how digital environments had a positive influence in developing spatial skills. Similarly, Wu et al. (2012) reinforced that first-person video games can enhance spatial visual skills. Moreover, studies in different disciplines have provided empirical and theoretical foundation on how VR technologies can positively affect neuroplasticity (e.g., Cheung et al., 2014; Coco-Martin et al., 2020; Levin, 2011). More important, the study by Lin et al. (2020) displayed how VR has an overall positive effect in design processes, but to increase the effect, more hands-on interaction is needed.

Summary

The design process has relied on traditional media tools, such as pencil and paper, to move the design process forward. These tools elicit the occurrence of creative sparks thanks to their attributes of ambiguity and density. Nonetheless, new generations of design students perceive these tools as less efficient and focus on more novel digital tools. These new digital tools are replacing traditional media and currently can be found in the design process from beginning to end. Hence, research is needed to better understand how these tools might affect the design process. More specifically, this study focused on VR, a widely accepted digital media tool that permits immersion in these new digital environments.

Cognition is a situated activity in which humans engage with their environment through the use of their bodies. In VR, the physical body is nonexistent; nonetheless, the mind can generate a connection with it through the concept of embodiment. This connection is achievable through the SoE, which comprises the sense of location, agency, and body ownership. Within the SoE, the VB permits researchers to manipulate different levels of immersion to affect presence and cognitive demand.

Presence is the sensation of being there while remaining elsewhere. Because cognition is situated and requires the interaction of the body, the deeper the presence in an immersive VR environment, the more naturally the participant will behave, similarly to the real world. Likewise, this behavior permits the liberation of CL in the environment, increasing the possibility of cognition in the performed task.

In design education, spatial skills and creativity are deemed critical for the design process. This study focused on the little-c's of creativity, such as those insightful moments within the design process that help move the process forward. Within an immersive VR environment, this study explored a logical approach to problem solving through the use of embodied actions that liberate cognitive load. These cognitive resources can then be destined to solve the design task while increasing spatial perception through visualization.

CHAPTER III

METHODS

Due to the interpretive nature of the design process, qualitative research has been the most common methodological approach to address research questions related to the design process. Researchers have gathered insight into the way creativity unfolds within the design process by multiple methods of registering the process and coding it. Moreover, researchers have conducted quantifying strategies such as linkography (Kan & Gero, 2008) or complex coding schemes, which can further be explained through quantitative analysis (Suwa et al., 1998). The research problem to tackle in this study suggests that one data source is sufficient to capture the impact of digital mediums in the conceptual stage of the design process; hence, an overall quantitative approach was proposed.

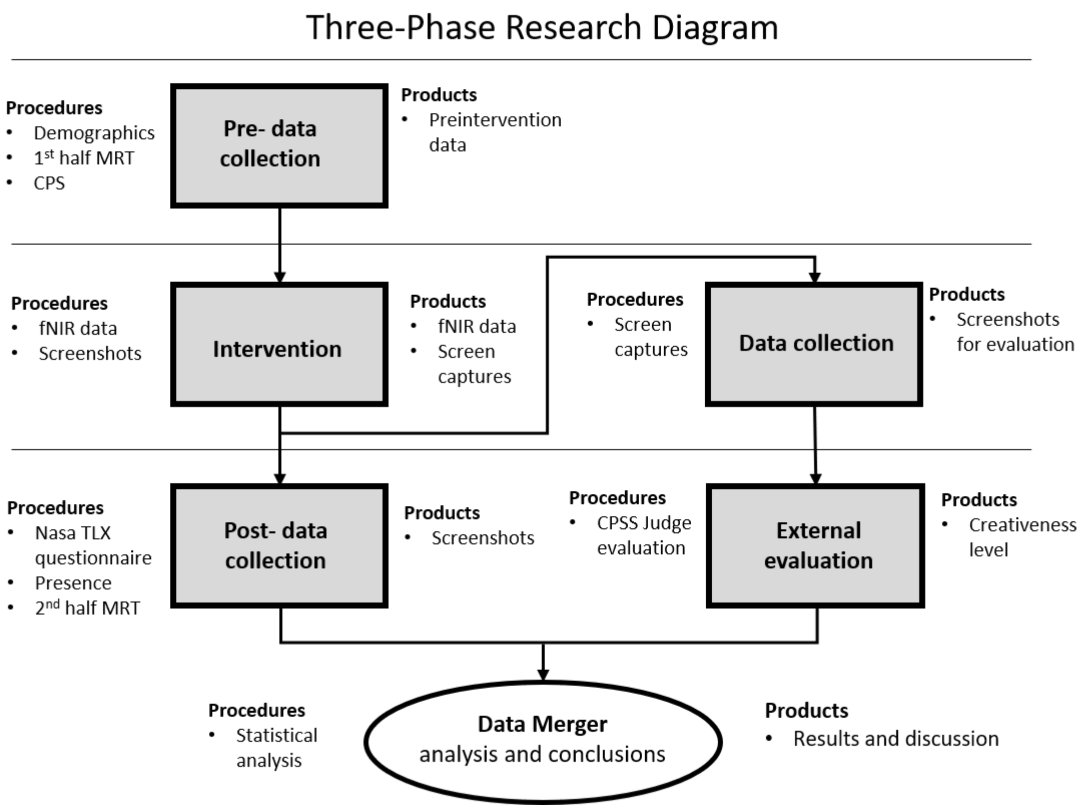
The rationale for selecting this approach was its pragmatic use. There is a long-standing debate between the different worldviews supporting the quantitative and qualitative realms. Nonetheless, pragmatism emerged as a worldview that permits the explanation of theoretical standpoints from diverse data perspectives (Morgan, 2007;

Tashakkori & Teddlie, 2008). According to Tashakkori and Teddlie (2008), pragmatism considers the truth to be *what works*.

The methodological approach that best suited this study's focus was a quantitative experimental design consisting of three phases of data capture. The first was done before the intervention, the second throughout the intervention, and the third after the intervention. All these phases together were defined as the *experiment*. Quantitative data was gathered in the preintervention phase from the CPS and the MRT. During the intervention, quantitative data was collected through the fNIR device. Postintervention, screenshots were collected and scored by external evaluators using the CPSS. Also, quantitative data was collected through the NASA-TLX (Hart, 2006; Hart & Staveland, 1988), presence questionnaires (Baren & IJsselsteijn, 2004), and the MRT (Nagy-Kondor, 2017; Vandenberg & Kuse, 1978). To control for bias between data sources, all data were analyzed independently and merged only for final analysis (see Figure 6).

Figure 6

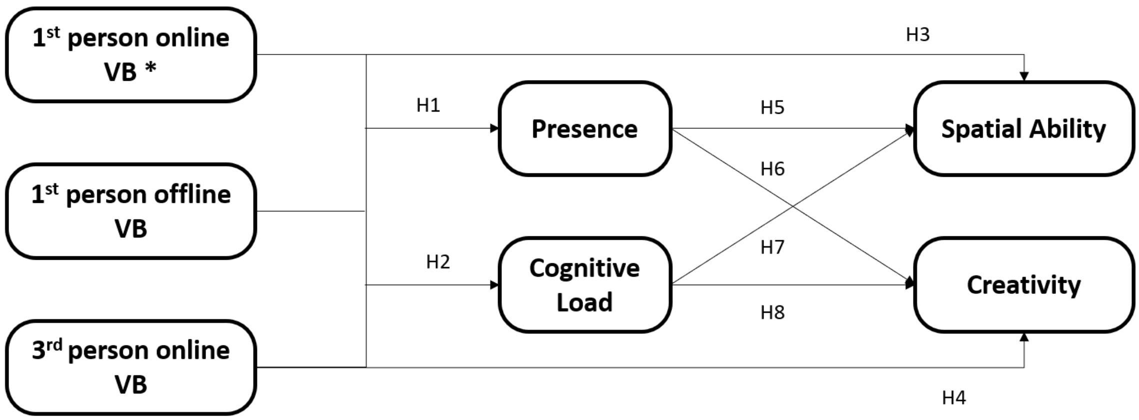
Research Diagram



This study selected a between-groups experimental setup to evaluate the independent variable (IV) of SoE composed of three levels of VB. The influence of this variable in the creative design process was assessed through the evaluation of creativeness of the designed outcomes and development of spatial abilities (see Figure 7).

Figure 7

Research Variables



Note. VB = Virtual Body

Research Questions and Hypotheses

Research Question 1:

How does the sense of embodiment (SoE) through the virtual body (VB) affect ideation in the creative design process?

RQ1.1: How does the VB affect the sense of presence?

RQ1.2: How does the VB affect the cognitive load?

RQ1.3: How does the VB affect the development of spatial abilities?

RQ1.4: How does the VB affect creativity of the outcome?

Research Question 2:

RQ2.1: How does presence affect the development of spatial abilities?

RQ2.2: How does the sense of presence affect the creativity of the designed outcome in the design process?

Research Question 3:

RQ3.1: How does cognitive load affect the development of spatial abilities?

RQ3.2: How does the cognitive load affect the creativity of the designed outcome in the design process?

Hypotheses for RQ1

- H1; The type of VB used in immersive VR environments affects the sense of presence.

  H_01: μ 1st person online = μ 1st person offline = μ 3rd person online
  H_11: μ 1st person online > μ 1st person offline > μ 3rd person online

- H2: The type of VB used in immersive VR environments affects the cognitive load.

  H_02: μ 1st person online = μ 1st person offline = μ 3rd person online
  H_12: μ 1st person online < μ 1st person offline < μ 3rd person online

- H3: The type of VB used in immersive VR environments affects the development of spatial abilities.

  H_03: μ 1st person online = μ 1st person offline = μ 3rd person online
  H_13: μ 1st person online > μ 1st person offline > μ 3rd person online

- H4: The type of VB used in immersive VR environments affects creativity in the design process.

  H_04: μ 1st person online = μ 1st person offline = μ 3rd person online

H_14: μ 1st person online > μ 1st person offline > μ 3rd person online

Hypotheses for RQ2

- H5: The sense of presence in immersive VR environments affects the development of spatial abilities.

  H_05: $\rho = o$

  H_15: $\rho \neq o$

- H6: The sense of presence in immersive VR environments affects creativity in the design process.

  H_06: $\rho = o$

  H_16: $\rho \neq o$

Hypotheses for RQ3

- H7: The demand of cognitive load in immersive VR environments affects the development of spatial abilities.

  H_07: $\rho = o$

  H_17: $\rho \neq o$

- H8: The demand of cognitive load in immersive VR environments affects creativity in the design process.

  H_08: $\rho = o$

  H_18: $\rho \neq o$

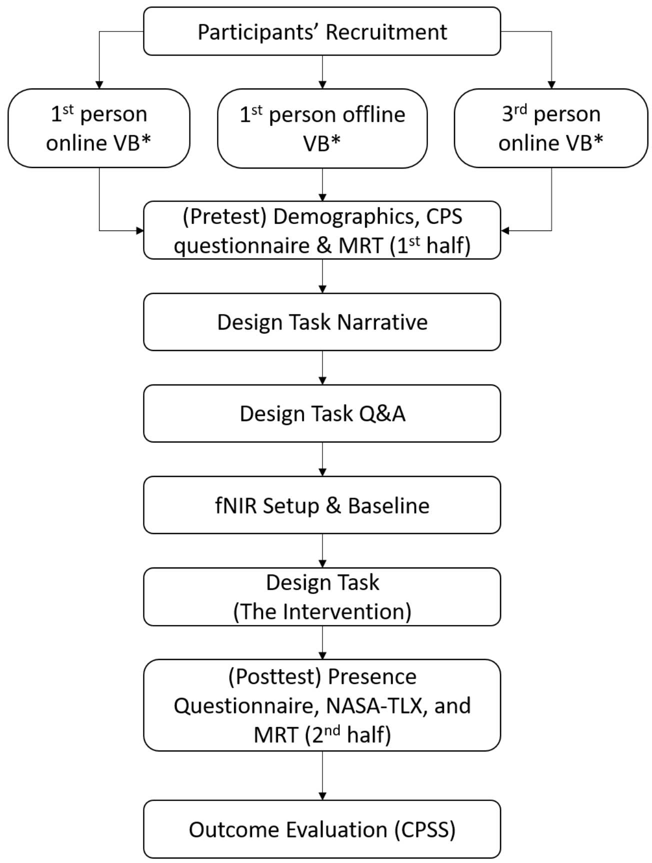
This study selected multiple assessment tools to evaluate the proposed relationship between variables. The chosen tools were the following:

- CPS as a self-report assessment tool used to measure the initial level of creativity of participants before the intervention (Kaufman & Baer, 2004).
- CPSS to account for the level of creativeness of the designed outcome (Christiaans, 2002).
- MRT to measure spatial visualization skills before and after the intervention (Nagy-Kondor, 2017; Vandenberg & Kuse, 1978).
- A presence questionnaire developed to measure the level of participants' perceived presence in the VR environment (Baren & IJsselsteijn, 2004).
- fNIR device to measure oxygenation levels in the brain accounting for cognitive load (Ayaz et al., 2013; Kaimal et al., 2017).
- NASA-TLX questionnaire to assess the perceived cognitive demand by participants in the given task (Hart, 2006; Hart & Staveland, 1988).

The study's design comprised a preintervention assessment, followed by the intervention consisting of a design problem to solve and finalized with a postintervention assessment. The design is illustrated in Figure 8.

Figure 8

Experimental Design



Note. vb = Virtual Body.
MRT = Mental Rotation Test.
CPS = Creative Personality Scale
CPSS = Creative Product semantic Scale

Sample Selection

Studies must address the debate between the type of sample and the type of research. This debate revolves around the concepts of probability sample, which uses a large number of participants randomly selected that enables findings that can be generalizable to a specific population, and purposive sample, which is deliberately selecting a group of participants according to intrinsic characteristics of research interest

(Teddlie & Yu, 2007). This study used a purposive sample due to its objective to explore creative outcomes in digital media environments (Gall et al., 2007).

This study used a single sample (Collins et al., 2007; Teddlie & Yu, 2007), guided by two strategies. First, design process studies frequently use purposive sampling to gather data, in part due to their specific interest in analyzing the way designers think and due to the vast amount of information generated from recordings and observations. Nonetheless, this study focused solely on the design outcome as an example of creativity within the design process. Second, to collect quantitative data, this study randomly assigned participants to one of the three conditions. Participants were students of a midwestern university located in the United States. Prescreening criteria was considered in the preintervention survey in which participants had to be over 18 years and identified their education level. No screening was carried out for any physical disability, such as, visual, auditory, or cognitive deficiencies. Expected sample recruitment was established at 20 participants per condition for an overall total of 60 participants.

Preintervention Data Capture and Analysis

Preintervention data were captured through the preintervention survey including demographics and CPS questions. The CPS accounted for the self-report level of creativeness of participants. Self-report scales are considered a reliable and straightforward way to identify creative personality traits (Hocevar, 1981). In addition to the pretest questionnaire, participants completed without time constraints the first half of an MRT measuring spatial abilities (Nagy-Kondor, 2017; Vandenberg & Kuse, 1978). Following the pre-experiment questionnaire, participants were handed in a brief that contained the instructions of the activity they were to perform in the VR environment.

Intervention Data Capture and Analysis

Once the brief was read and any questions were answered on behalf of the investigator, participants interacted in the VR environment to become familiar with the actions and movements. In this small interaction, participants did not engage designing, and the main purpose was to control for any bias that may occur due to participants' unfamiliarity with the environment. Afterward, a psychophysiological device was attached to the participants (see Figure 9).

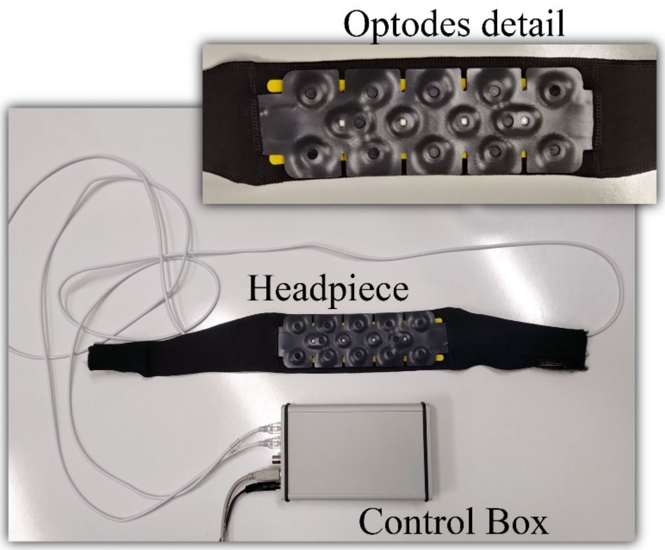
Figure 9

Attachment of Functional Near-Infrared (fNIR) Device onto Participants

The psychophysiological equipment was a Biopac F2000 series fNIR device, with an 18-optode headband RXFNIR-2000-18 located over the scalp on the participants' forehead (see Figure 10).

Figure 10

Functional Near-Infrared Spectroscopy (fNIR) Device With Headband

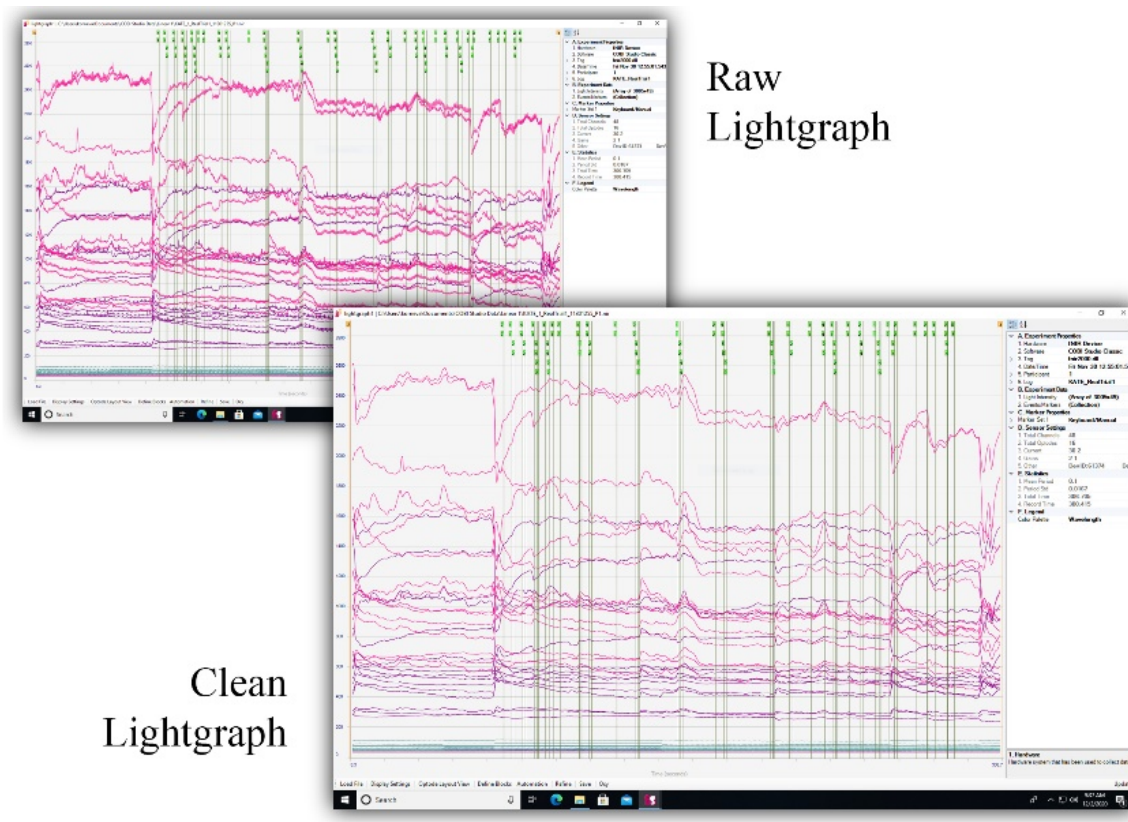


The software to collect the fNIR data was CobiModern provided by Biopac. fNIRSOFT was used for data processing and analysis. The intensity of the ambient light was controlled for the experimental environment according to the initial readings captured in the Cobi software. Once the fNIR device was attached to participants, data collection started with the baseline taken for a minimum of 1 min in a relaxed seating position with the eyes shut. Afterward participants were to open their eyes, stand up, and engage in the VR interaction following the directions previously read from the brief. Markers were generated along the data collection process to pinpoint specific events such as baseline and VR interaction boundaries.

The fNIR quantitative was collected in the Cobi software in the form of lightgraphs, which were filtered using the 2-Hz low-pass filter predetermined by fNIRSOFT (Ayaz, 2010). After this first filter was applied, data were processed through a sliding-window motion artifact rejection (SMAR) filter (Ayaz et al., 2010). *Artifacts* are defined as involuntary movements that can contaminate the data. This SMAR filter was applied with a window size of 2 Hz and upper and lower thresholds of 25 and 3, respectively (see Figure 11).

Figure 11

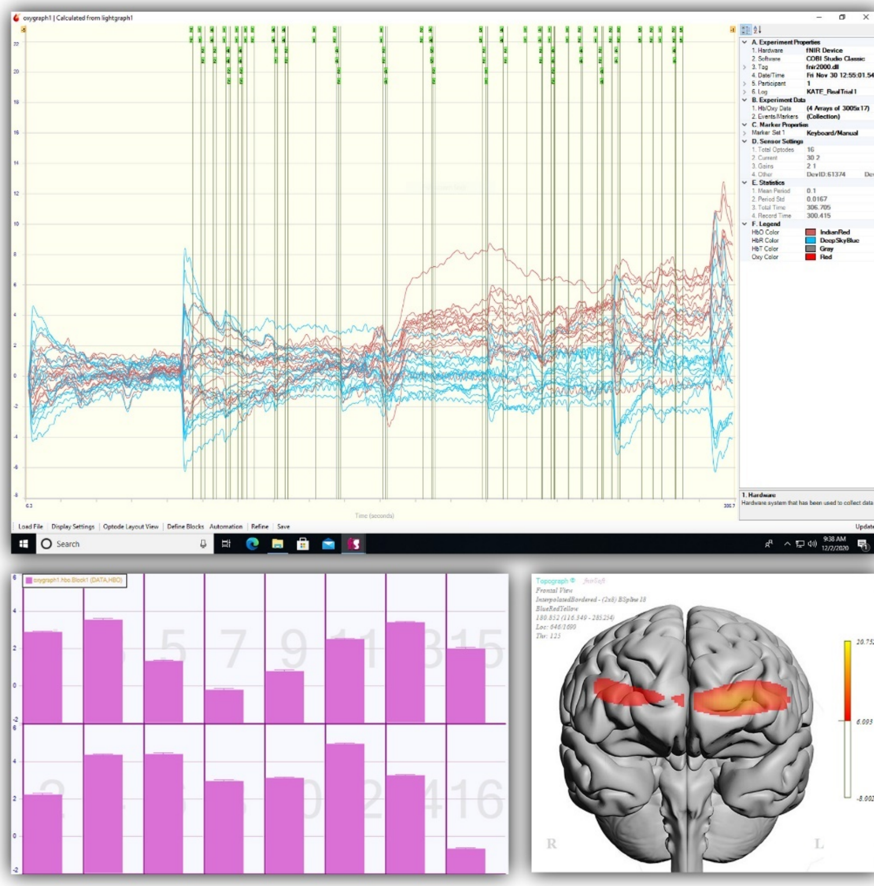
Raw and Clean Lightgraph



Processed lightgraphs were used to generate oxygraphs and brain topography through fNIRSOFT (see Figure 12). The collected baseline was used to calculate the oxygraphy.

Figure 12

Oxygraph, Bar Graph, and Brain Topography



Besides the fNIR data, once participants finished the interaction in the VR environment, screenshots of the design outcome were captured for scoring through the CPSS by external evaluators.

Postintervention Data Capture and Analysis

After the VR intervention session, participants completed an online post-experiment survey containing the NASA-TLX and presence questionnaires. Also, participants completed the second half of the MRT, once again without time restrictions. Quantitative data resulting from this survey were statistically analyzed through a one-way analysis of variance (ANOVA), repeated measures ANOVA, bivariate correlation, and linear regressions using SPSS software, version 24. Post hoc analyses were done using Tukey pairwise comparisons when homogeneity of variances was met and Dunnett C when it was not. Assumption of normality of variances was accounted for through Levene's test of normality. Also, mean comparisons for the fNIR data were done using software SPSS, version 24. All statistical analysis used an α level of significance of .05.

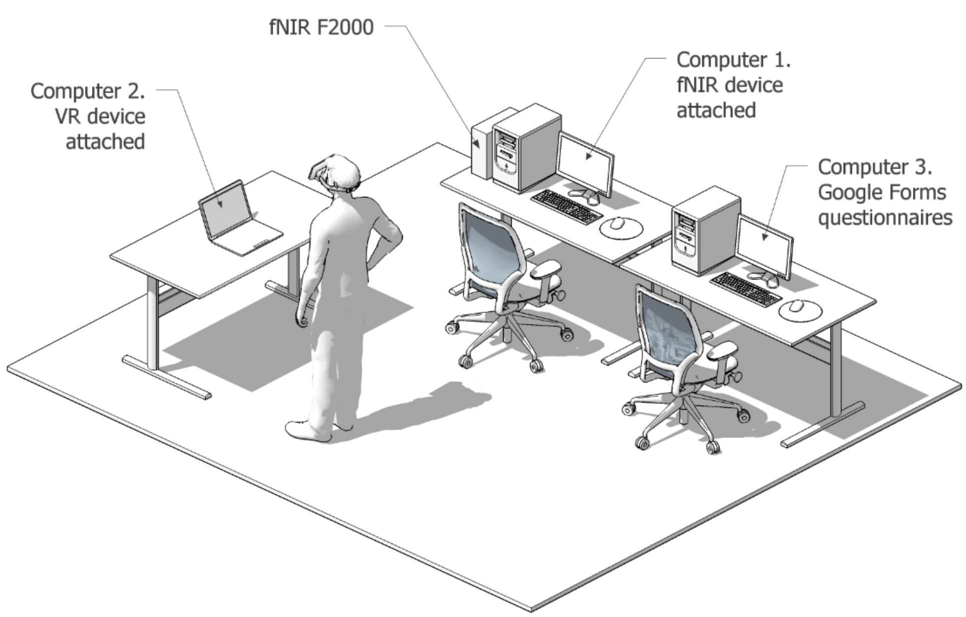
At the same time, one data source was obtained during the experiment but analyzed postintervention. This data assessed the level of creativeness of the experiment's outcome. After interaction in the VR environment, multiple screenshots were captured of the participant's proposed layout. These screenshots captured the arrangement of the modules in the designated space. To do so, multiple perspectives and points of view were used. Three screenshots per participant were selected as most accurate in portraying the designed spatial arrangement of the modules. These images were grouped on a board pertaining to each participant for revision and evaluation. A panel of evaluators evaluated three dimensions of each proposal (novelty, resolution, and elaboration and synthesis) through the CPSS (Christiaans, 2002). To ensure dependability and address overall legitimacy, the panel of evaluators consisted of three evaluators (Onwuegbuzie & Johnson, 2006). Moreover, these were carefully selected to ensure as much homogeneity as possible (Baer, 2010). The specific requirements were to be a design educator with above master's degree, and to have taught design studio courses to undergraduate students for at least 5 years of professional practice. Each evaluator assessed independently all 72 outcomes using the CPSS and only after they had completed the evaluation, were scores compared and analyzed for interrater reliability.

Study Setup

The study setup used three computers. The first computer recorded all the activity through a Biopac fNIR 2000 model device connected to an 18-optode sensor band headpiece RXFNIR-2000-18 composed of light sources and photodetectors. The Cobi Modern software was used for data capture and fNIRSOFT software was used for data visualization and processing. The second computer used for the VR experience included an HTC Vive HMD. This computer was equipped with Steam VR software, and the intervention was an executable file that, once opened, projected automatically in the HMD. This computer was used to capture screenshots of the design outcome. The third computer did not require any specific characteristics and was solely used to complete the online questionnaires through Google Forms (see Figure 13).

Figure 13

Study Setup



Design Exercise

The design exercise was carefully planned to be open for creativity, simple, and above all, not strenuous to participants. A critical aspect considered was to provide a design brief that engaged spatial ability and required creative problem-solving skills. Previous research supports that these aspects engage the brain's frontal lobes and right hemisphere (Feist, 2010). Moreover, spatial skills and creative outcome align with the relevance that these two domain-specific characteristics have for design education (Allen, 2010; Cho, 2017; Zacks et al., 2000). Finally, the main dimension of embodiment to manipulate was that of agency (Kilteni et al., 2012). The design brief considered three key factors in its formulation.

The first factor was the level of difficulty in terms of cognition and cognitive load. The main consideration was to keep the design problem similar to an exercise held in conventional studio courses for design students. Guided by this premise, the manipulation of objects in the VR environment addressed the principles of dominant, subdominant, and subordinate objects to generate compositions (Hannah, 2002). Objects varied in size and shape, permitting the use of multiple axes in creating compelling arrangements. Besides, the design brief considered the three principles proposed by DeSutter and Stieff (2017) when designing interventions that elicit embodied cognition. Actions in the VR environment must be intentional, following the scaffolding principle, and must use epistemic movements aiming to reduce cognitive load. Actions were predictive in terms of the laws of physics, so when participants dropped something in the VR environment, gravity affected it. Finally, actions occurred in an imaginary physical scenario that used novel visualization techniques to stimulate creativity.

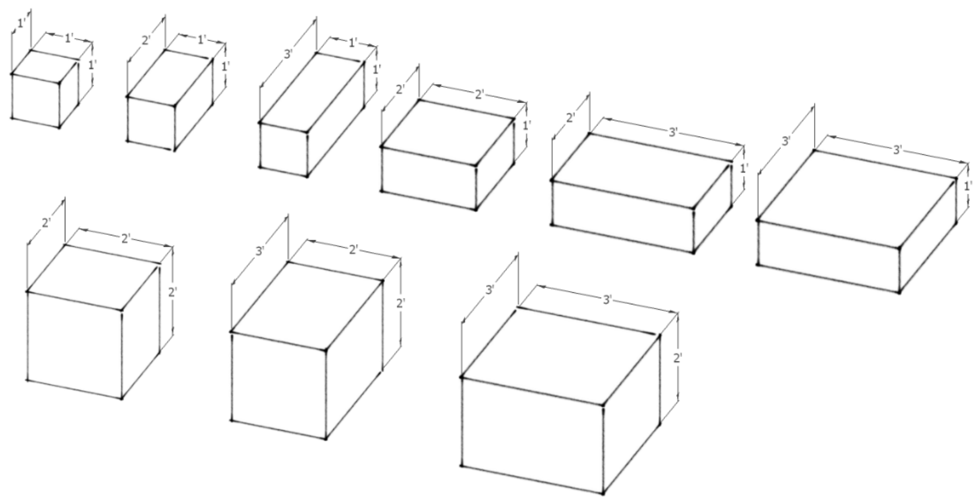
The second factor considered immersion characteristics of the intervention to provide an efficient sense of presence in participants. Of the multiple dimensions that compose presence, this study focused on four: spatial presence, self-presence, engagement and realism (Lombard & Jones, 2015b). These dimensions were addressed by the use of an HMD that projects immersive VR environments to enhance participants' sensation of "being there" while physically remaining somewhere else (Biocca et al., 2003; Lee, 2004; Witmer & Singer, 1998). In this VR environment, participants had the capability of perceiving themselves by total or partial avatars from multiple points of view, permitting the illusion of body ownership (Galvan Debarba et al., 2017). To stimulate engagement, the proposed activity took place in an imaginary futuristic scenario. This scenario was a space station based on Mars in which participants arranged some rectangular containers of different sizes under given restrictions of content, material, and location. Finally, even though the activity took place in an imaginary scenario, the interaction used high-quality immersive graphics projected through the HMD, and these were consistent with the laws of physics. These attributes were selected to provide authenticity, tackling the presence dimension of realism (Lee, 2004).

The third and final factor considered was the inspirational attributes of the task. As mentioned earlier, the task aims to elicit the engagement of the participants. As said by Csikszentmihalyi and Nakamura (2014), engagement is a critical aspect of flow and creativity. Because creativity is the ability to solve problems that generate novel and useful solutions (Runco, 2008), the design brief proposed a problem to be addressed by the participants through a functional solution in a nonexistent environment. This solution required the use of spatial abilities to offer a sculpture-like solution, or physical arrangement, composed of containers.

This study was based on the nine-square grid problem frequently used in architectural and interior design studio courses (Hopfenblatt & Balakrishnan, 2018). In this study, the task was to arrange multiple containers within a small (12’ × 8’) space station space (see Figure 14). These modules comprised a system of nine different volumes manufactured in three different materials. The first material was a thermal material that could manipulate the temperature of the content or the exterior surface. The second material was a very robust and lightweight material based on Kevlar and carbon fiber blending that had ballistic resistance and was extremely lightweight. The final material was a new composite based in Aramid and new polymeric structures that permitted structural rigidity but surface flexibility. One of the main attributes of this new modular system was that the modules could interlock by generating contact between the faces. The logic behind these constraints was to provide participants with a complex problem that needed logical thinking to propose a design solution.

Figure 14

Container Module Options

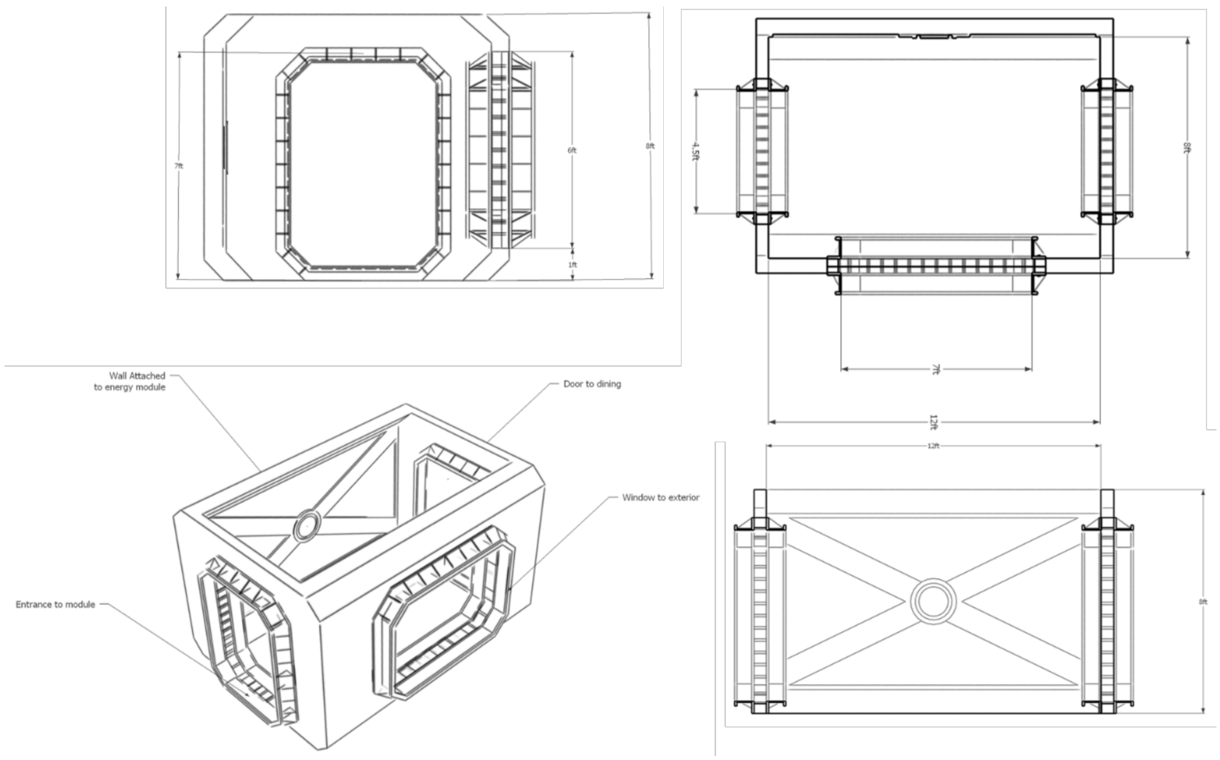


Three essential contents were stored in each container. The first content was flammable oxygen pipettes used for spacewalks and outdoor activities. The second content was medical supplies intended for emergencies or daily well-being. The third content was constituted of biodigestible elements, more specifically food and water reserves intended for everyday consumption.

The space station floor design had two entrances in the minor walls, one of which connected to the outside of the space station and the other to a combined commons and dining area. One of the main walls of this space was attached to the energy module of the space station, and the opposite wall there was a panoramic window with a superb view of the earth and the stellar surroundings (see Figure 15).

Figure 15

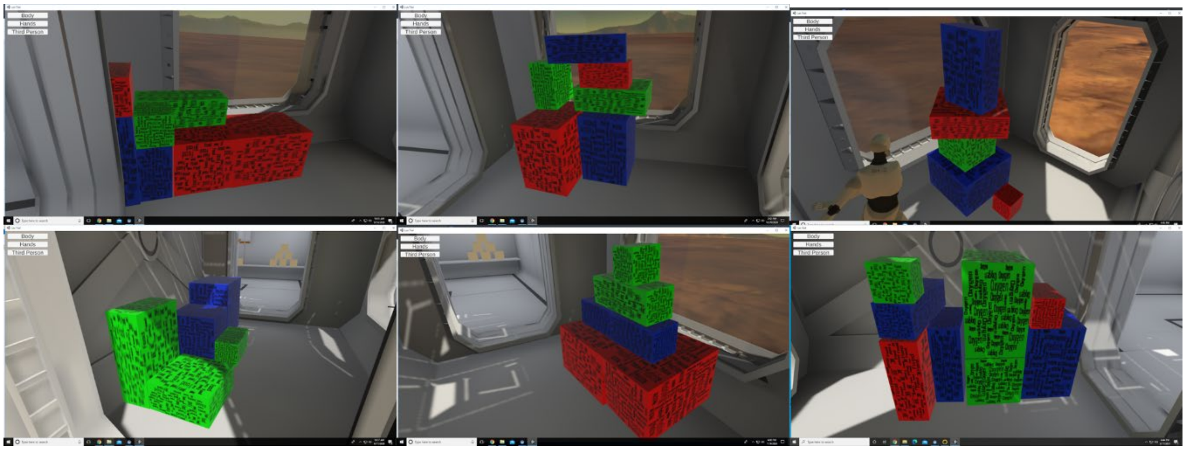
Isometric View and Spatial Diagrams



Participants choose as many modules as they want from the available sizes in any of the three proposed materials. In each container, they stored one of the available contents. Participants were encouraged, but not limited to generate a sculpture-like distribution of the modules that could have some alternative use besides storage (see Figure 16).

Figure 16

Examples of Outcomes



To develop the design exercise, this study used Unity 2019.2.14f1 software and addressed participants' interaction through an HTC Vive HMD plus two HTC 2018 controllers (see Figure 17).

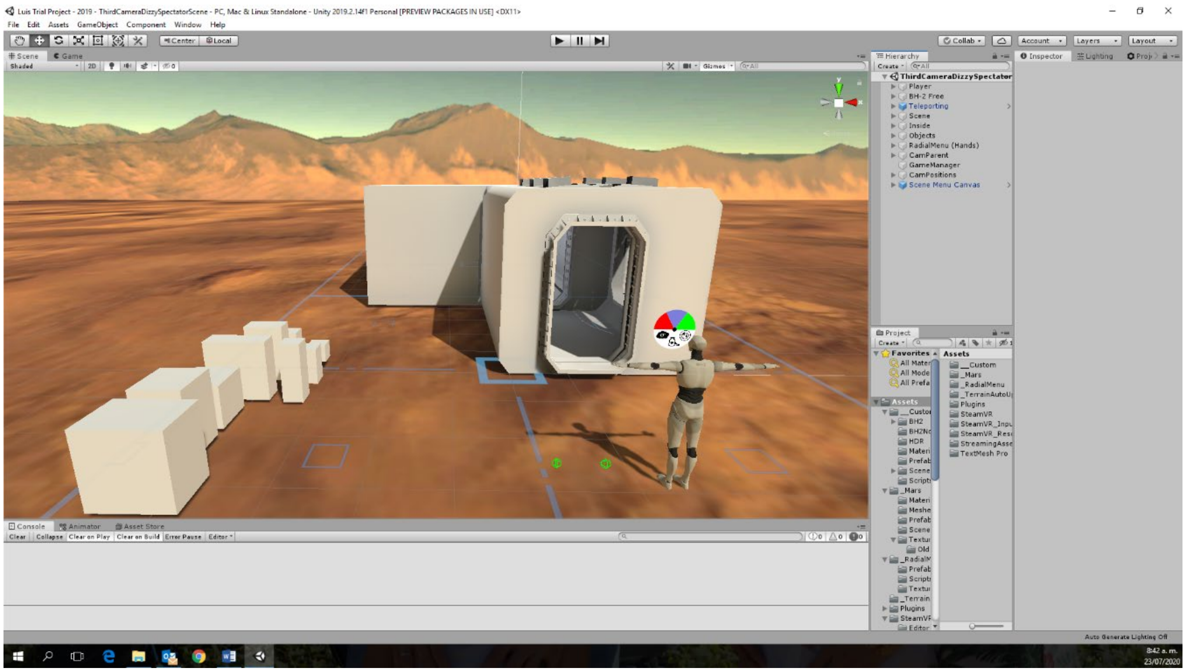
Figure 17

Participants

The virtual setup consisted of a Mars-like physical landscape with some space station modules located in front of the participants and the containers on the side. In the exterior view, participants walked in a limited space around the space station modules. Within the interior, participants walked freely but were constrained by the walls and objects that generated physical boundaries (see Figure 18).

Figure 18

Design Intervention Scene

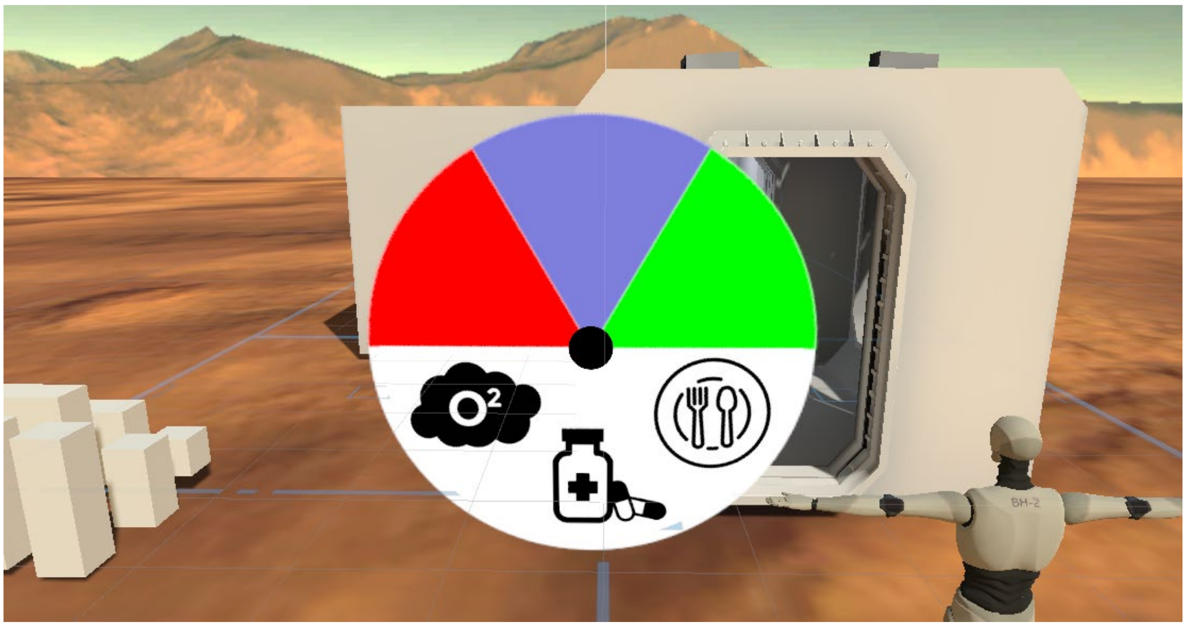


The design exercise used avatars for the three selected VB setups (see Table 1). As previously stated, avatars are humanized representations of the body in VR environments (Etemad-Sajadi, 2016). The first and second conditions were in a first-person perspective with the difference that the former did not have a representation of the VB, but the latter did. The third condition used a third-person perspective, whereby participants can see their avatars in an out-of-body experience. It was critical for the development of this design intervention that the selected perspectives permitted the illusion of body ownership (Galvan Debarba et al., 2017).

The two HTC controllers permitted the manipulation of the container modules in the virtual space. For this purpose, the trigger button in both controllers enabled participants to grab and release the modules. The left controller's trackpad allowed the function of teleporting around the space. The right controller's trackpad had a radial menu that facilitated the selection of material and content of each module (see Figure 19).

Figure 19

Radial Menu for Material and Content Selection



The three upper sections enabled the selection of the material (red = thermal resistant, blue = ballistic resistant, and green = flexible); whereas, the lower three parts, the content (flammable oxygen, medical supplies, and food and water). Participants needed to only point the controller to the container module they wanted to change. After that, they interacted with the right controller's trackpad to select the material and content. The targeted module changed color according to the selected material. Also, a bitmap appeared on the module's surfaces with a text that specifies the content. The designed textures considered visibility features regardless of the position of the modules (see Figure 20).

Figure 20

Materials' Textures Projected in the Modules

Instruments

This study used multiple instruments to acquire relevant data to address the proposed research questions and hypotheses.

Demographic Information

Demographics questions were developed and included in the first part of the pretest online questionnaire. These questions were only used to support the descriptive statistics of the sample of participants.

Creative Personality Scale

The CPS was developed by Kaufman and Baer (2004) in their process of assessing creativity through self-report tools for different domains. It consists of 20 items that are scored on a 5-point Likert scale that ranges from 1 (*very inaccurate*) to 5 (*very accurate*). The CPS displayed a significant correlation with students' self-reported creativity, grade point average, and SAT scores, enhancing the construct validity of the tool (Kaufman & Baer, 2004). Moreover, a further study including the CPS supported the importance of self-reported measures to assess creativity (Silvia et al., 2012).

Creative Product Semantic Scale

The CPSS is an evaluation scale for creative outcomes based on three dimensions: novelty, resolution, and elaboration and synthesis (Christiaans, 2002). Each dimension is assessed through multiple pairs of adjectives that intend to evaluate the creativity of the evaluated proposal. In addition to the pair of adjectives that Christiaans defined for each dimension in the original CPSS, this study added some new pairs on the basis of the study by Demirkan and Afacan (2012) to address creativity in design education.

A group of evaluators evaluated the design outcome on a 5-point Likert scale using the CPSS. This condition aligned with that elucidated by Csikszentmihalyi (1999) when he argued that creativity is not an outcome of the individual generating the creative outcome, but rather a perception of the gatekeepers who accept such outcome into the general domain. Finally, it was critical for validity purposes that the selected evaluators were as homogeneous as possible (Christiaans, 2002).

Mental Rotation Test

Vandenberg and Kuse (1978) initially introduced the Mental Rotation Test (MRT), and it has been widely used in research aiming to measure spatial ability (Nagy-Kondor, 2017). This test presents to participants a figure composed of cubes in an original position, and beside it, four different figures, two of which depict the initial figure in two rotated positions. Participants were to select which two figures of the available four corresponded to the original figure. This test had 20 questions and was divided into two halves; each half was presented to participants in pencil and paper before and after the intervention.

Presence Questionnaire

The presence questionnaire was based in the meta-analysis developed by Baren and IJsselsteijn (2004) on the presence questionnaires. In this analysis, they covered 20 questionnaires used in research to measure multiple aspects of presence. This study constructed a presence questionnaire based on questions covering four dimensions of presence: sense of location (presence), spatial attributes (appearance), sense of ownership (interaction), and embodiment and body ownership (embodiment). In total, 26 questions were selected and answered using a 5-point Likert scale. Also, an overall presence appraisal question was included in which participants rated their level of "being there" on a scale from 1 to 100.

Functional Near-Infrared Spectroscopy

An fNIR device uses light to measure levels of oxygenation in the brain to account for brain activity (Ayaz et al., 2013). Major levels of oxygen demand in the blood correlate to higher brain activity and hence, major cognitive load (Ayaz et al., 2013; Kaimal et al., 2017)

By using fNIR, the cognitive load can be measured through light saturation and deoxygenation of the brain (Izzetoglu et al., 2011). Studies have also shown that by using the fNIR device, one is able to determine cognitive load as well as an emotional response through the reading of the prefrontal lobe (Kaimal et al., 2017).

NASA-TLX Questionnaire

The NASA-TLX questionnaire introduced by Hart and Staveland (1998) is an instrument for measuring cognitive load after performing a given task. The initial test is composed of two parts that, once combined, generate a general score. The first part of the procedure is a weighting process of 15 pairs of possible combinations. These combinations refer to six subscales: mental demands, physical demands, temporal demands, own performance, effort, and frustration (Chandrasekera, 2015). The second part comprises multiple subscales in which participants select the amount of effort required for the given task. This study applied only the second part of the NASA-TLX questionnaire procedure supported in the findings of Hart (2006).

CHAPTER IV

RESULTS

The present study used three conditions of the VB in IVR environments to assess their effect on presence, CL, spatial abilities, and creativity. To do so, pre-, and post-questionnaires were used supported by a psycho physiological device. External evaluators assessed the level of creativity of the designed outcome. This study obtained institutional review board approval, and all Centers for Disease Control and Prevention guidelines for social distancing and sanitizing pertaining to the CoViD-19 pandemic were accounted for in the data collection process. Data collection started in August 2020 and ended in March 2021. The data were collected in the Mixed Reality Lab at Oklahoma State University.

Basic Demographics

All participants were adult students at the undergraduate or graduate level in a midwestern university located in the United States. A sample size of N = 72 was obtained, composed of 81.9% women and 18.1% men. Ages were distributed as follows: 84.7% from 18–24 years; 8.3% from 25–30 years; and 6.9% from 31–40 years. Most of the sample was composed of junior-level students (30.6%), followed by senior-level

(20.8%), graduate (19.4%), and finally sophomore and freshmen levels (15.3% and 13.9%, respectively; see Table 2).

Table 2

Demographics of the Sample

Condition	Gender, *n* (%)				Age, y (%)					
	Female		Male		18–24		25–30		31–40	
1	19	(79.2)	5	(20.8)	21	(87.5)	0	(0)	3	(12.5)
2	21	(87.5)	3	(12.5)	20	(83.3)	4	(16.7)	0	(0)
3	19	(79.2)	5	(20.8)	20	(83.4)	2	(8.3)	2	(8.3)
Totals	59	(81.9)	13	(18.1)	61	(84.7)	6	(8.3)	5	(6.9)

Condition	Academic Year, *n* (%)										
	Freshmen		Sophomore		Junior		Senior		Graduate		Total
1	3	(12.5)	6	(25.0)	8	(33.3)	4	(16.7)	3	(12.5)	24
2	4	(16.7)	3	(12.5)	7	(29.2)	5	(20.8)	5	(20.8)	24
3	3	(12.5)	2	(8.3)	7	(29.2)	6	(25.0)	6	(25.0)	24
Total	10	(13.9)	11	(15.3)	22	(30.6)	15	(20.8)	14	(19.4)	72

All participants were summoned for a 1-hr time frame to conduct the experiment without time constrictions. This time was established through a pilot test run with two participants before starting the data collection process. These two participants' data were not included in the data analysis presented here.

During the experiment, in the VR-interaction data collection process, four markers were generated to further define data blocks for analysis. The first two markers corresponded to the beginning and end of the baseline; the remaining two, to the start and finish of the VR activity (tackling the design brief). These markers were used afterward in fNIRSOFT to identify two blocks of information. The first block (baseline) was used to calculate the oxygraphs, and the latter block delimited the experiment's boundaries for further analysis. This second block of data was of particular interest for this study because it was the length of time participants engaged in the experiment within the immersive VR environment to tackle the brief. The average time for this block was 20.67 min (*SD* = 10.52 min; see Table 3).

Table 3

Time Distribution

Condition	Participants, *n*	*M*, min	*SD*, min
1	24	21.20	11.15
2	24	17.17	7.89
3	24	23.64	11.54
Total	72	20.67	10.52

Creativity Baseline

For the validity of this study, it was relevant to ensure that all participants reported a similar level of creativity between groups before the experiment. To do so, the CPS was used to assess whether any differences between groups existed before the data analysis. Hence, the CPS was administered as part of the pre-experiment questionnaire to all participants. This instrument was developed by Kaufman and Baer (2004) as a tool to assess creativity through self-report methods for different domains. Twenty items were scored using a 5-point Likert scale ranging from 1 (*very inaccurate*) to 5 (*very accurate*). For analysis, the 20 scores were added for a possible highest score of 100. The total sample size had a mean score of 62.39 (*SD* = 5.16). The three conditions were also scored independently with a mean score for Condition-1 of 60.75 (*SD* = 4.53), Condition-2 of 63.29 (*SD* = 4.93), and Condition-3 of 63.13 (*SD* = 5.77; see Table 4). Given that this study aimed to find no statistically significant differences in self-reported creativity between groups, a one-way ANOVA was conducted and revealed no statistical significance between means, $F(2,69) = 1.86$, $p = .16$.

Table 4

Creativity Baseline

Condition	*n*	*M*	*SD*
1	24	60.75	4.53
2	24	63.29	4.93
3	24	63.13	5.77
Total	72	62.39	5.16

Note. No statistical significance was found between means.

The Effect of VB on Presence and CL

This section aims to present the results of VB on the sensation of presence and CL, which ultimately affects creativity and spatial abilities. The study investigated the following research questions using pre- and post- experiment questionnaires, in addition to an fNIR device.

RQ1.1: How does the VB affect the sense of presence?

RQ1.2: How does the VB affect the cognitive load?

RQ1.3: How does the VB affect the development of spatial abilities?

RQ1.4: How does the VB affect creativity of the outcome?

- H1: The type of VB used in immersive VR environments affects the sense of presence.
- H2: The type of VB used in immersive VR environments affects the cognitive load.

- H3: The type of VB used in immersive VR environments affects the development of spatial abilities.
- H4: The type of VB used in immersive VR environments affects creativity in the design process.

Effect of VB Over Presence

The post-experiment questionnaire was based on the presence questionnaire compendium (Baren & IJsselsteijn, 2004) and the Witmer and Singer (1998) questionnaire. This presence questionnaire covered four dimensions of presence: sense of location (*presence*), spatial attributes (*appearance*), sense of ownership (*interaction*), and SoE and body ownership (*embodiment*). The questionnaire totaled 26 items that used a 5-point Likert scale. Of the 26 questions, 15 questions were divided among *presence*, *appearance,* and *interaction,* with five questions for each dimension. The remaining 11 questions accounting for the *embodiment* dimension were distributed between embodiment (five) and body ownership (six). Moreover, the first three dimensions (*presence*, *appearance*, and *interaction*) related to the characteristics of the overall presence of the intervention (Witmer & Singer, 1998), whereas the remaining dimension (*embodiment*) related more to the way the participant felt in the given space (Kilteni et al., 2012). Also, an *overall presence appraisal* question was included in which participants rated their level of "being there" on a scale from 1 to 100.

All 26 questions were added per individual for a possible score of 25 points for each of the first three dimensions (*presence, appearance*, and *interaction*), plus an additional 55 points for the last dimension (*embodiment*). This did not include the *overall presence appraisal* score, which could yield another 100 points for a grand total of 230 points for the complete questionnaire. After data inspection in SPSS using the box plot interquartile range (IQR), three outliers were detected and eliminated from the *overall presence appraisal* question (see Table 5).

Table 5

Presence Questionnaire

Dimension	Condition	*n*	*M*	*SD*
Presence	1	24	20.50	2.59
	2	24	19.96	2.07
	3	24	19.08	2.53
	Total	72	19.85	2.48
Appearance	1	24	18.71	2.03
	2	24	19.25	2.67
	3	24	16.17	2.92
	Total	72	18.04	2.87
Interaction	1	24	18.21	2.36
	2	24	17.88	2.88
	3	24	17.71	2.45
	Total	72	17.93	2.54
Embodiment	1	24	39.96	6.30
	2	24	38.88	6.21
	3	24	36.67	6.66
	Total	72	38.50	6.45
Overall presence appraisal	1	22	85.23	19.46
	2	24	80.13	13.86
	3	23	73.48	20.47
	Total	69	77.33	18.36

Note. The highest possible overall score was 230, which breaks down to 130 points for 26 Likert-style questions on the four dimensions and 100 points for the overall presence appraisal scale.

In addition, factor analysis was calculated to corroborate the consistency of the previously discussed dimensions (see Table 6).

Table 6

Factor Analysis

Variable	Cronbach's α
Intervention overall presence	.80
Presence	.72
Appearance	.65
Interaction	.73
Embodiment	.85

Multiple ANOVAs were conducted to reject the null hypothesis H1 that VB has no effect on presence. The three conditions were evaluated on how they affected the four dimensions of presence. The *presence* dimension had no statistical significance between conditions, $F(2,69) = 2.11$, $p = .12$. The dimension of *appearance* had statistical significance between conditions, $F(2,69) = 9.82$, $p = .00$. Post hoc analysis using a Tukey pairwise comparison elicited that Condition-3 had significant differences with Condition-1 ($p = .00$) and Condition-2 ($p = .00$), but no differences were found between Condition-1 and Condition-2 ($p = .74$). A moderate effect size (.48) and high power ($1-\beta = .95$) were obtained. The dimension of *interaction* displayed no statistical significance between conditions, $F(2,69) = 0.24$, $p = .79$. Finally, the dimension of *embodiment* displayed no statistical significance between conditions, $F(2,69) = 1.65$, $p = .19$.

Also, an ANOVA was conducted between the conditions for the *overall presence appraisal* from participants with statistical significance between conditions, $F(3.66) = 3.62$, $p = .03$. Because homogeneity of variances was not met and the null was retained, A post hoc analysis using the Dunnett C pairwise comparison concluded that Condition-3 had significant differences with Condition-1. A moderate effect size (.31) and high power ($1-\beta = .63$) were obtained.

Last, it was of interest to assess whether there was a difference between conditions for the dimensions relevant solely to the intervention (*presence, appearance,* and *interaction*). For this purpose, the scores of these three dimensions were added, and mean scores of 57.4 (SD = 5.47), 57.08 (SD = 6.15), and 52.96 (SD = 52.96) were obtained for Condition-1, Condition-2, and Condition-3, respectively. An ANOVA was carried out with statistical significance, $F(2,69) = 4.01$, $p = .02$. Post hoc analysis using a Tukey pairwise comparison elicited that Condition-3 had significant differences with Condition-1 ($p = 0.04$), and with Condition-2 ($p = .05$), but no statistically significant differences were found between Condition-1 and Condition-2 ($p = .98$). A moderate effect size (.22) and moderate power ($1\text{-}\beta = .36$) were obtained.

After complete analysis, null hypotheses H1 was rejected. All conditions affected the sense of presence. Nonetheless, Condition-3 displayed a lower level of presence than did Condition-1 and Condition-2.

$$H_0 1: \mu 1^{st} \text{ Condition-1} = \mu 2^{nd} \text{ Condition-2} = \mu 3^{rd} \text{ Condition-3}$$

$$H_1 1: \mu 1^{st} \text{ Condition-1} > \mu 2^{nd} \text{ Condition-2} > \mu 3^{rd} \text{ Condition-3}$$

Effect of VB Over CL

The NASA-TLX questionnaire was included in the post-experiment questionnaire as an instrument to measure cognitive load after performing the task in the VR environment. This questionnaire was introduced by Hart and Staveland (1998), and its reliability has been widely supported (Hart, 2006; Hoonakker et al., 2011; Xiao et al., 2005). This study only applied the second part of the NASA-TLX questionnaire procedure supported in the findings of Hart (2006). The NASA-TLX questionnaire is composed of six different aspects of task performance scored on a 5-point Likert scale.

For analysis, all scores of the six aspects were added for a possible maximum score of 30 points (see Table 7). An overall question regarding activity difficulty was included using a 9-point scale where 1 corresponded to *very, very low mental effort* and 9 to *very, very high mental effort* (see Table 8).

Table 7

NASA-TLX

Condition	*n*	*M*	*SD*
1	24	15.79	2.83
2	24	14.25	2.30
3	24	16.54	3.17
Total	72	15.53	2.92

Table 8

Activity Difficulty

Condition	*n*	*M*	*SD*
1	24	5.92	1.44
2	24	5.38	1.09
3	24	5.71	1.19
Total	72	5.67	1.26

To reject the null hypothesis H2 that VB does not affect CL, an ANOVA was carried out for the NASA-TLX between the three conditions with statistically significant results, $F(2,69) = 4.18$, $p = .02$. Post hoc analysis using a Tukey pairwise comparison elicited that Condition-3 had significant differences with Condition-2 ($p = .01$), but not with Condition-1 ($p = .62$). No statistically significant difference was found between Condition-1 and Condition-2 ($p = .14$) A moderate effect size (.46) and high power ($1-\beta = .94$) were obtained.

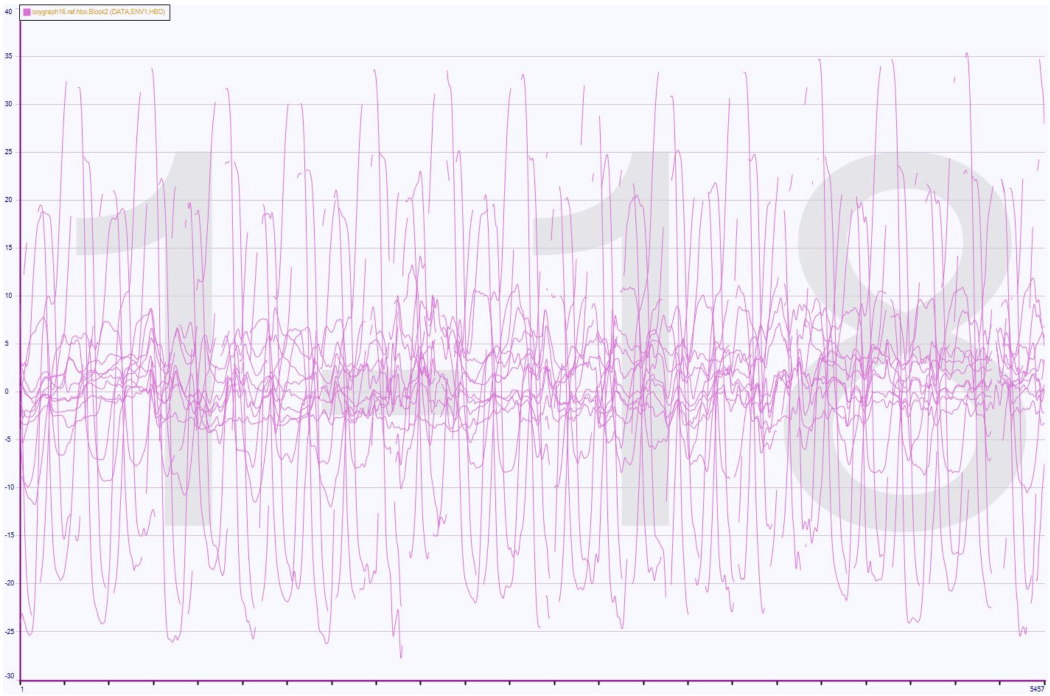
Moreover, because task difficulty was included in the post-experiment questionnaire, an ANOVA was carried out between the perceived task difficulty by participants and the three conditions with no statistically significant results, $F(2,69) = 1.14$, $p = .32$.

Ultimately, the scores of task difficulty and NASA-TLX were added together to evaluate an overall appraisal of CL. The mean scores were 21.71 ($SD = 3.39$), 19.63 ($SD = 3.14$), and 22.25 ($SD = 3.86$), for Condition-1, Condition-2, and Condition-3, respectively. An ANOVA was carried out with statistical significance between means, $F(2,69) = 3.81$, $p = .27$. Post hoc analysis using a Tukey pairwise comparison elicited that Condition-3 had significant differences with Condition-2 ($p = .03$), but not with Condition-1 ($p = .85$). No statistically significant differences were found between Condition-1 and Condition-2 ($p = .10$) A moderate effect size (0.34) and high power ($1-\beta = .72$) were obtained.

To corroborate and expand on the data gathered from the NASA-TLX, this study used an fNIR device to account for oxygenation levels in the brain's prefrontal lobe (Ayaz et al., 2013; Kaimal et al., 2017). Oxygraphs were calculated on the basis of the lightgraphs collected through the Cobi software. Oxigraphs were visually inspected, and those corrupted were deleted and not considered for analysis (see Figure 21). Corrupted oxygraphs result from external light, most possibly from movement of the HMD that affects the light receptors at the moment of data collection.

Figure 21

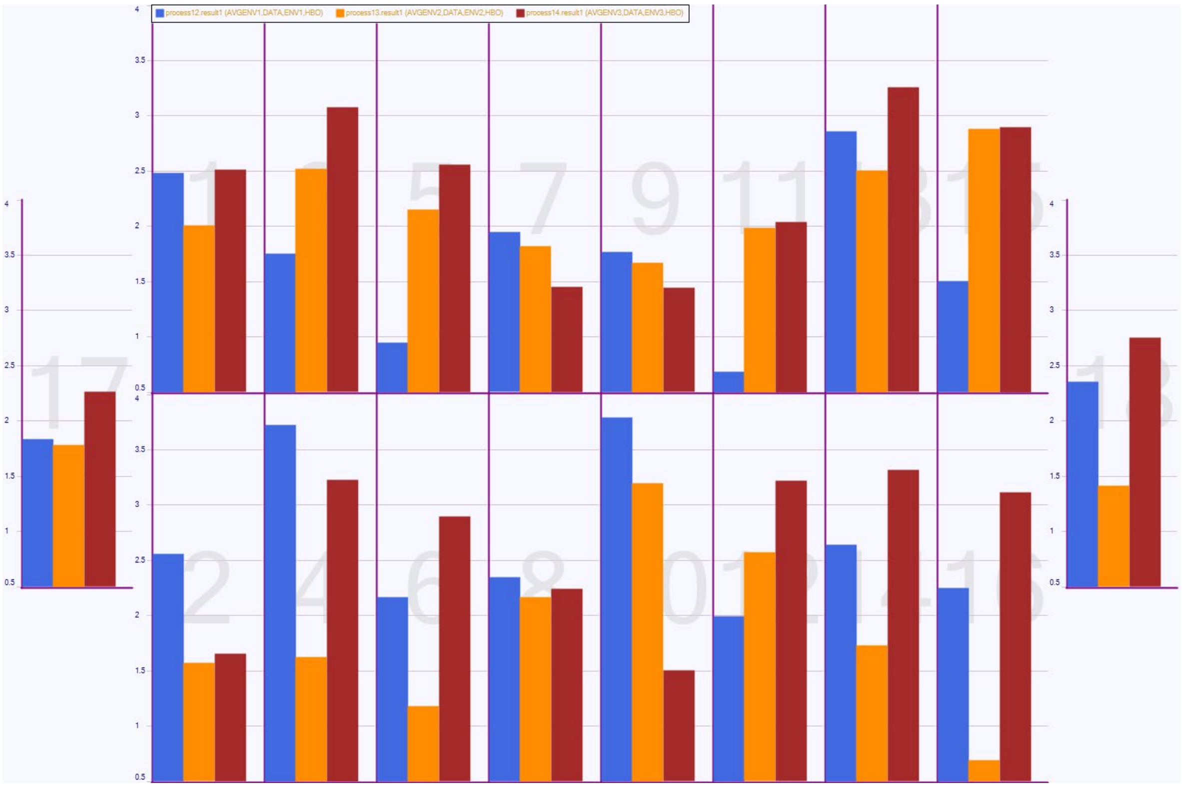
Example of Corrupted Oxygraph



The first step in fNIR data analysis was to create bar graphs using the fNIRSOFT for visual inspection. After visually inspecting the graph, Condition-1 displayed higher levels in optodes OP2, OP4 and OP6 – OP10 for a total of seven optodes from the available 16 (43.8%). Condition-2 did not display higher levels in any of the 16 optodes (0%). Condition-3 displayed higher levels in optodes OP1, OP3, OP5, OP6 and OP11 – OP16, for a total of ten of the available 16 optodes (62.5%). Optodes OP17 and OP18 were used as a control for the device and were not accounted for in data analysis (see Figure 22).

Figure 22

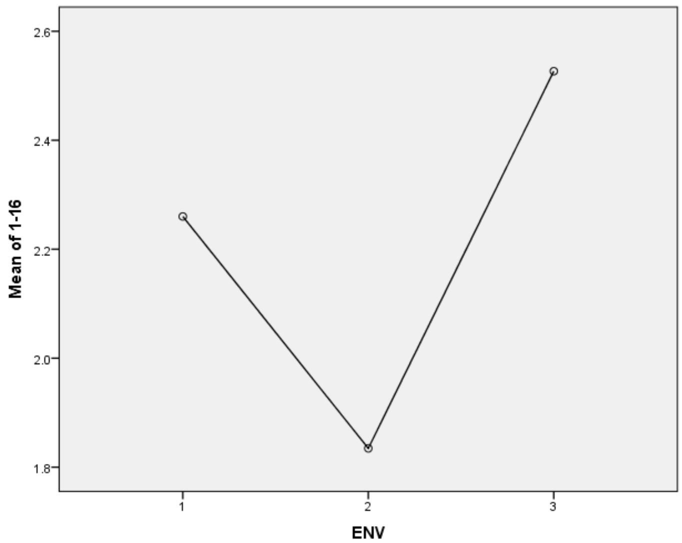
fNIRSOFT Data Bar Graph



To enable further analysis, the average of the 16 optodes was calculated for each participant for statistical comparison in SPSS, version 24. An ANOVA was conducted between these averages and the three conditions. No statistical significance between conditions was found, $F(2,62) = 1.72$, $p = .16$. Nonetheless, the scatterplot for the means is consistent with the information visualized in the fNIRSOFT bar graphs used for visual inspection (see Figure 23).

Figure 23

Scatterplot Optode Average per Condition

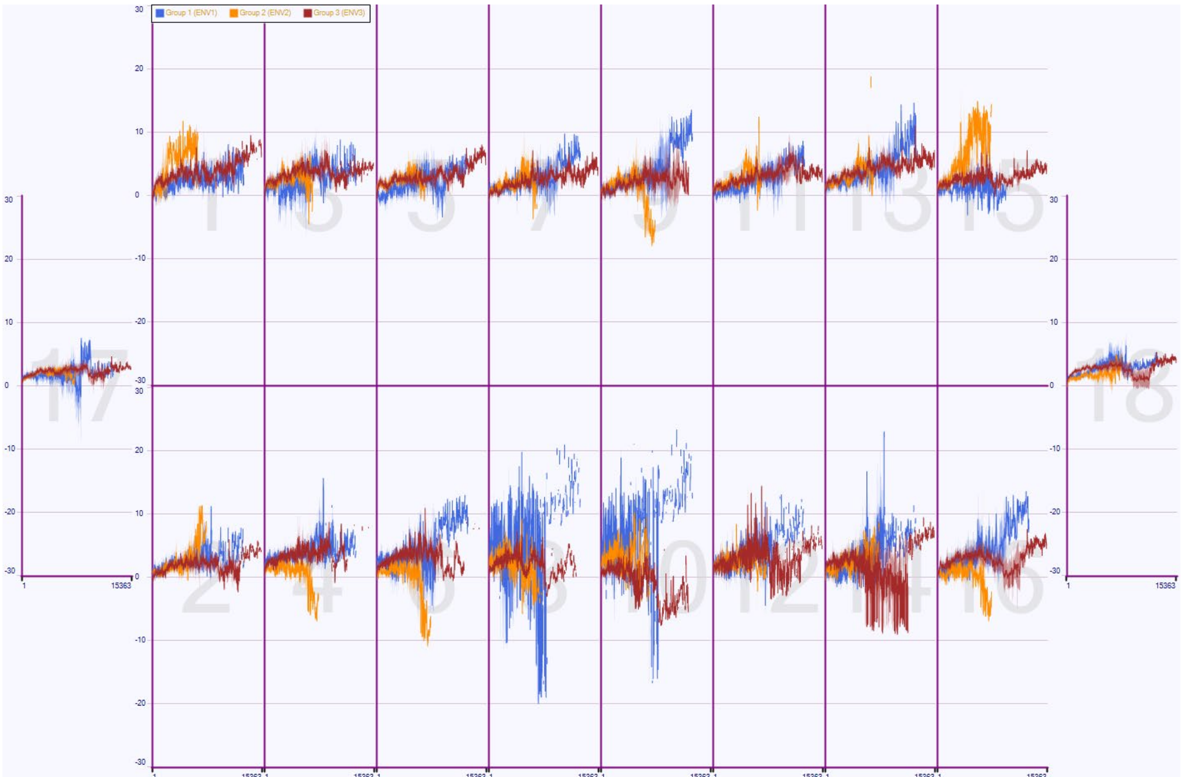


Furthermore, a correlation analysis was conducted between the post-experiment NASA-TLX questionnaire and the optodes data. A weak positive linear correlation between the two variables was found with no statistical significance, $r(62) = 0.18$, $p = .23$.

Temporal analysis was conducted using the fNIRSOFT to visualize the evolution of optode activity throughout the VR interaction. A temporal graph discerning the data between the optodes was generated to compare the three environments as an overlay. Blue corresponds to Condition-1, orange to Condition-2, and red to Condition-3 (see Figure 24). Data variation was seen in the lower optodes as a result of proximity between the headband and the HMD.

Figure 24

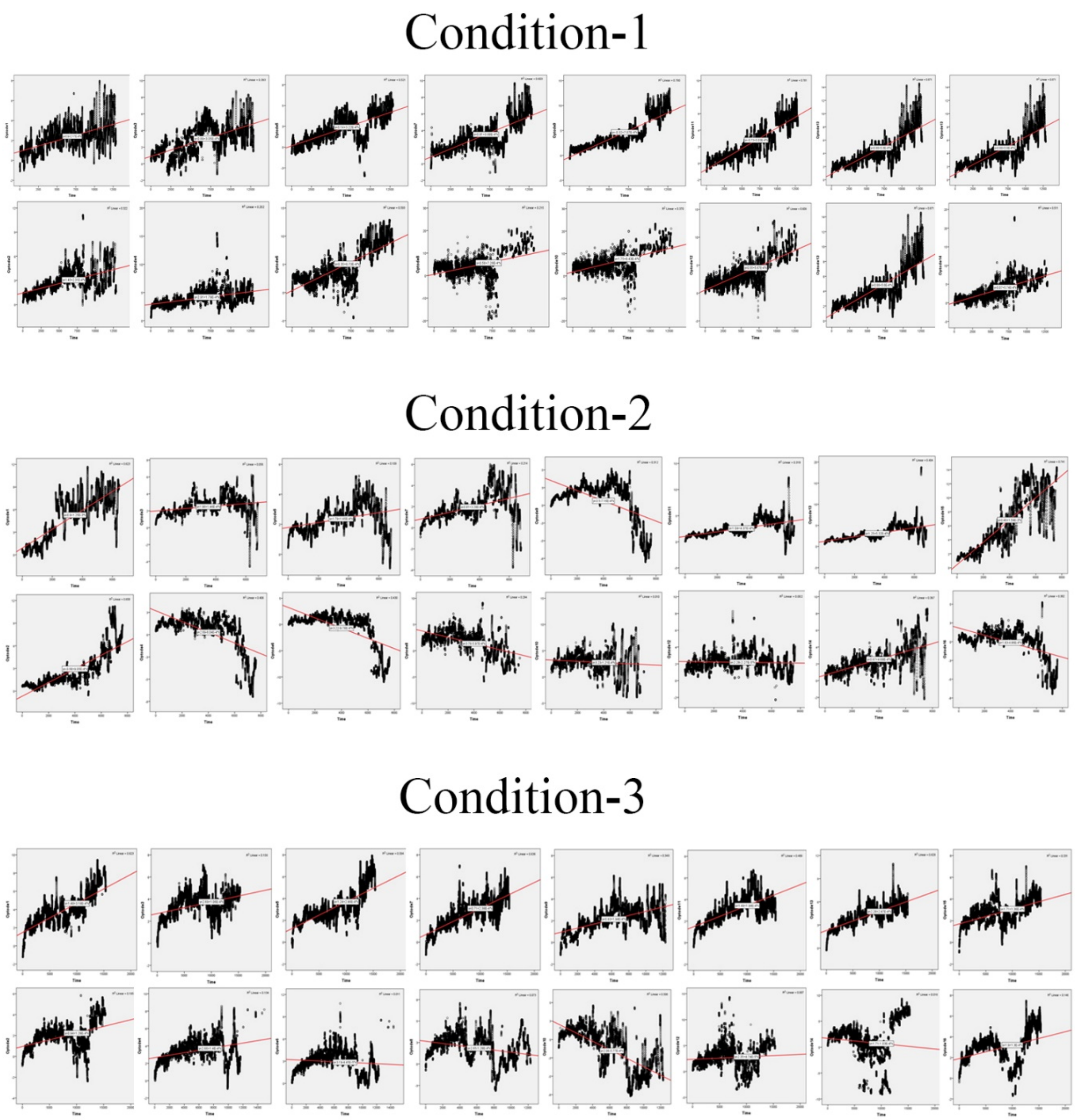
Temporal Graph per Optode Between the Three Conditions



Temporal data from each optode on the three conditions was exported for further analysis. Scatterplots were generated, and lines of best fit were added to observe the tendencies of each optode within each environment over time. For Condition-1, all optodes displayed an increasing tendency through time (100%). For Condition-2, optodes OP4, OP6, OP8, OP9, OP10, OP12, and OP16 displayed a decreasing tendency through time, and the remaining optodes displayed an increasing tendency (56.3%). For Condition-3, a total of 12 optodes presented an increasing tendency through time (81.3%); the exceptions were optodes OP6, OP8, OP10, and OP14 (see Figure 25).

Figure 25

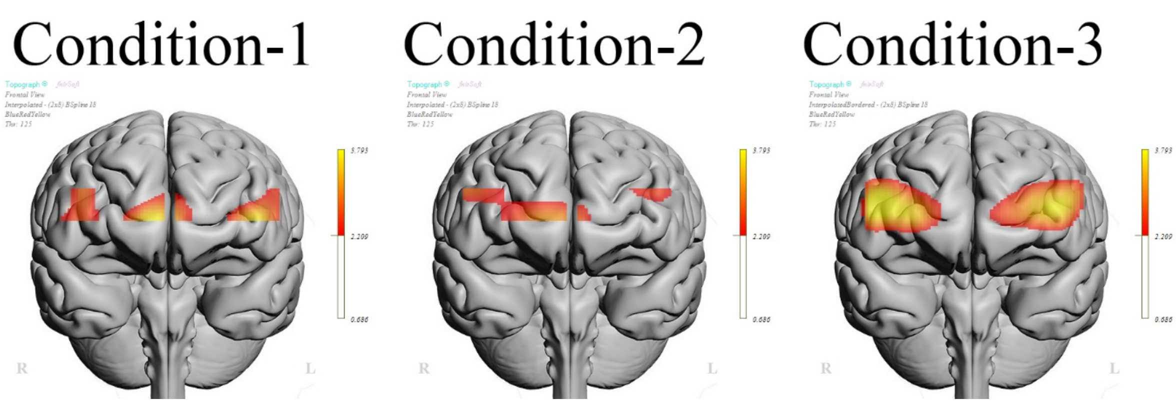
Temporal Scatterplots and Lines of Best Fit



Finally, data were processed through fNIRSOFT to create brain topography for each of the conditions for visualization. Through brain topography, it can be observed that Condition-1 and Condition-2 highly activated both brain hemispheres, whereas Condition-2 mainly increased the right hemisphere. Also, different levels of cognitive demand can be seen through the color scale, in which yellow stands for high activation and red represents diminished activation (see Figure 26).

Figure 26

Brain Topographs of the Three Conditions



After complete analysis, null hypothesis H2 was rejected. All conditions affected CL. Condition-2 displayed lower levels of CL and was the only one that diminished in time in comparison to the remaining two conditions.

$H_0 2$: $\mu 1^{st}$ Condition-1 = $\mu 2^{nd}$ Condition-2 = $\mu 3^{rd}$ Condition-3

$H_1 2$: $\mu 1^{st}$ Condition-1 < $\mu 2^{nd}$ Condition-2 < $\mu 3^{rd}$ Condition-3

Effect of VB Over Spatial Ability

The MRT has been widely used in research aiming to measure spatial ability (Nagy-Kondor, 2017). A figure composed of cubes in an original position is presented to participants. Beside it, four different figures depict the initial figure in rotated positions and two do not correspond to that initial figure at all. Participants are to select the two correct figures of the available four. This test has 20 questions; for this study, it was divided into half. The first six questions of each half were presented to participants in pencil-and-paper format before and after the intervention. Given that two figures are chosen for each question, scoring each correctly selected figure with 1 point will give a possible total score of 12 points for the half. The first step for data analysis was to calculate the means and standard deviations for the pre- and post-experiment MRT scores for each of the environments (see Table 9).

Table 9

Descriptives Pre- and Post-experiment MRT

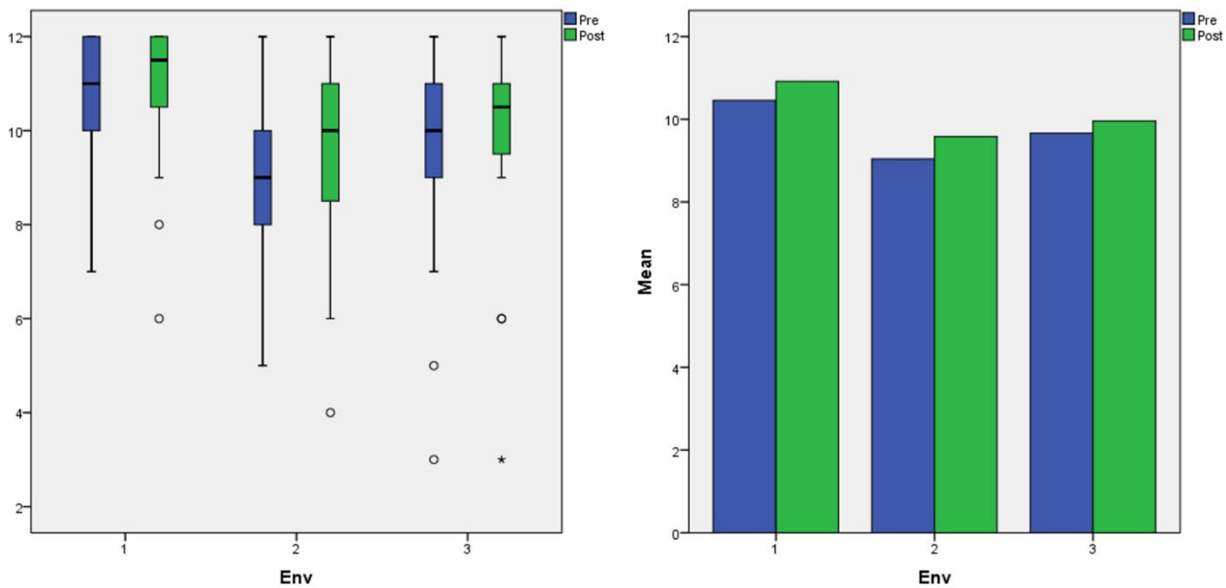
Condition	MRT	*n*	*M*	*SD*
1	Pre	24	10.46	1.44
	Post	24	10.92	1.55
	Diff		*0.46*	*1.66*
2	Pre	24	9.04	1.78
	Post	24	9.58	2.16
	Diff		*0.54*	*1.69*
3	Pre	24	9.67	2.16
	Post	24	9.96	2.25
	Diff		*0.29*	*1.26*
Total	Pre	72	9.72	1.92
	Post	72	10.15	2.04

Note: diff = difference

Box plots and bar graphs were developed to visualize differences in pre- and post-experiment MRT for the three conditions (see Figure 27). A repeated measures ANOVA for the pre- and post-experiment MRT was conducted among the three conditions and revealed statistical significance, $F(2,69) = 5.52$, $p = .22$. Post hoc analysis using a Tukey pairwise main effects comparison displayed statistical significance between Condition-1 and Condition-2 ($p = .023$) but not between each of those and Condition-3 ($p = .21$). No statistical significance was found between Condition-2 and Condition-3 (p = .51). A small effect size was detected (.12), and the overall power was moderate (1-β = .52).

Figure 27

Box Plots and Bar Graphs Among Three Conditions



After complete analysis, null hypotheses H3 was rejected. All conditions affected spatial ability. Overall, regardless of the specific condition, there was a statistically significant increase in spatial abilities for the complete sample.

H_03: $\mu 1^{st}$ Condition-1 = $\mu 2^{nd}$ Condition-2 = $\mu 3^{rd}$ Condition-3

H_13: $\mu 1^{st}$ Condition-1 > $\mu 2^{nd}$ Condition-2 > $\mu 3^{rd}$ Condition-3

Effect of VB Over Creativity

The interest of this study was not to evaluate the level of creativity of the process, but rather to measure the creativity of the outcome as an indicator of creativeness. For this reason, three evaluators with similar backgrounds evaluated the design outcome on a

5-point Likert scale using the CPSS. The CPSS is based on three dimensions: novelty, resolution, and elaboration and synthesis, and each dimension was assessed through multiple pairs of adjectives (Christiaans, 2002). In addition to the pair of adjectives that Christiaans defined, this study added some new pairs based on the study by Demirkan and Afacan (2012).

The first step for data analysis was to assess the interrater reliability. An interrater percentage of agreement of 61% was obtained between evaluators. A Cronbach's α for consistency between the evaluators' scores was also measured (α = .83). This type of measure is frequently used to examine the consistency among different raters scoring the same individual (Liao et al., 2010). The CPSS has a total of 20 items with a maximum score of 5 points each, for a grand total of 100 possible points. Final scores for each participant were added, and means were calculated for each condition (see C).

Table 10

CPSS Overall Scores

Condition	*n*	*M*	*SD*
1	24	45.66	12.80
2	24	42.20	11.01
3	24	37.02	11.11
Total	72	41.68	12.06

An ANOVA was conducted between the three means for each condition with statistically significant results, $F(2,70) = 3.38$, $p = .03$. Post hoc analysis using a Tukey pairwise comparison elicited that Condition-3 had significant differences with Condition-1 ($p = .03$) but not with Condition-2 ($p = .38$). No statistical significance was found between Condition-1 and Condition-2 ($p = .91$). A moderate effect size was detected (.29), and the overall power was high with $1\text{-}\beta = .58$.

For further analysis, the CPSS scores were separated among the three dimensions: novelty, resolution, and elaboration and synthesis (see Table 11).

Table 11

CPSS Dimensions' Scores

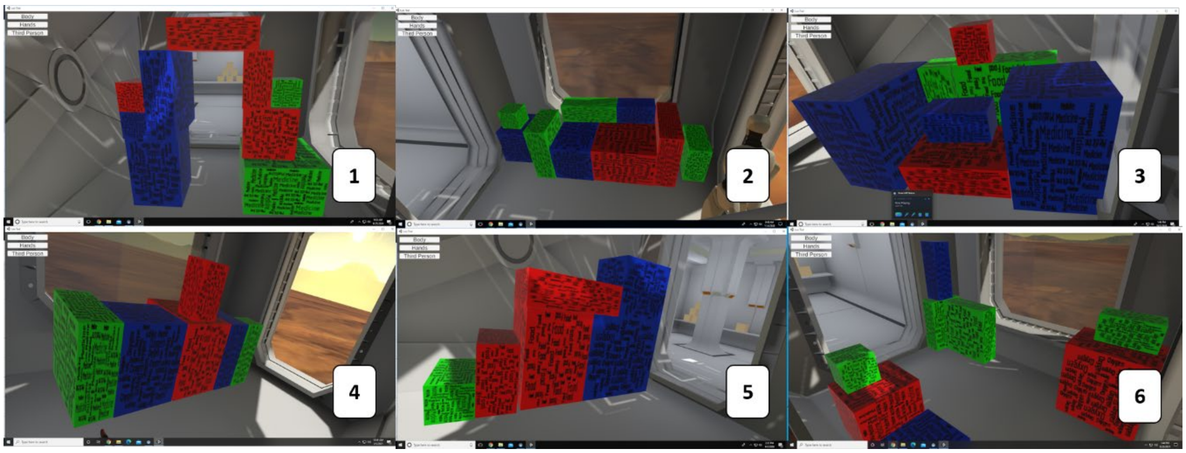
Dimension	Condition	*n*	*M*	*SD*
Novelty	1	24	16.67	4.19
	2	24	15.57	3.88
	3	24	15.91	3.51
Resolution	1	24	15.56	5.77
	2	24	14.39	4.69
	3	24	12.41	4.91
Elaboration and synthesis	1	24	16.77	5.70
	2	24	15.36	5.34
	3	24	12.20	5.04

An ANOVA was conducted between the three conditions for each of the previous dimensions of the CPSS. No statistical significance was found for *novelty* or *resolution*, $F(2,69) = 0.62$, $p = .54$; $F(2,70) = 2.02$, $p = .14$. Nonetheless, there was statistical significance for the elaboration and synthesis dimension, $F(2,69) = 4.21$, $p = .01$. Post hoc analysis using a Tukey pairwise comparison elicited that Condition-3 had significant differences with Condition-1 ($p = .01$) but not with Condition-2 ($p = .13$). No statistically significant differences were found between Condition-1 and Condition-2 ($p = 1.00$). A moderate effect size was detected (.37), and the overall power was high ($1\text{-}\beta = .80$).

The best outcomes were selected on the basis of the CPSS scores to illustrate to the reader of this study the different possibilities of designed outcomes. This selection was made until all conditions had at least one representative (see Figure 28). Images number 1 and 3–5 are outcomes of Condition-1, whereas images 2 and 6 are outcomes of Condition-3 and Condition-2, respectively.

Figure 28

Examples of Experiment Designed Outcomes



Null hypotheses H4 was rejected after complete analysis. All conditions influenced the creativity of the outcome. Condition-3 negatively affected creativity in comparison with Condition-1. No differences were found between Condition-1 and Condition-2, or between Condition-2 and Condition-3.

$H_0 4$: $\mu 1^{st}$ Condition-1 = $\mu 2^{nd}$ Condition-2 = $\mu 3^{rd}$ Condition-3

$H_1 4$: $\mu 1^{st}$ Condition-1 > $\mu 2^{nd}$ Condition-2 > $\mu 3^{rd}$ Condition-3

The Effect of Presence on Spatial Abilities and Creativity

The objective of this section is to present the results of presence on spatial abilities. The study investigated the following research questions using the presence questionnaire and an MRT and CPSS.

RQ2.1: How does presence affect the development of spatial abilities?

RQ2.2: How does the sense of presence affect the creativity of the designed outcome in the design process?

- H5: The sense of presence in immersive VR environments affects the development of spatial abilities.
- H6: The sense of presence in immersive VR environments affects creativity in the design process.

Effect of Presence Over Spatial Abilities

A multiple regressions model was estimated to evaluate whether the post-experiment questionnaire scores in *embodiment, total presence*, and *overall perceived presence* could predict *spatial abilities* (MRT). The weak positive linear relationship between *embodiment, total presence*, *overall perceived presence,* and *spatial abilities* was statistically significant, $F(2,65) = 2.94$, $p = .03$. Nonetheless, in this model, only 8% of the variance in spatial abilities was accounted for in *embodiment, total presence*, and *overall perceived presence*. $R^2 = .12$, adjusted $R^2 = .07$. Outliers and influentials were retained: ZRESID, SRESID, SDRESID, Cook's Beta, DFBETA, and DFBETAS. Tests of homogeneity of variances and normality of residuals were conducted.

A second model was run, eliminating residuals (ZRESID, SRESID, SDRESID). No influentials were deleted (Cook's Beta, DFBETA, and DFBETAS). This model once again displayed a weak positive linear correlation with statistical significant results, $F(2,51) = 4.49$, $p = .00$. In this model, 20% of the variance in spatial abilities was accounted for in *embodiment, total presence*, and *overall perceived presence*. $R^2 = .45$, adjusted $R^2 = .20$. Tests of homogeneity of variances and normality of residuals were conducted.

When looking at unique contributions of *embodiment, total presence*, and *overall perceived presence* in variance of *spatial abilities*, only *overall perceived presence* displayed a significant unique contribution accounting for 17% of the variance, $t(51) = 3.57$, $p = .00$). In contrast, non-statistically significant unique contributions for *embodiment* and *total presence* accounting for 1% and 2% of the variance, $t(53) = .08$, $p = .94$; $t(52) = .17$, $p = .74$, were respectively determined.

After analysis, null hypothesis H5 was rejected. *Spatial ability* was positively affected by *embodiment, total presence,* and *overall perceived presence.*

$H_0 5$: There is no relationship between variables.

$H_1 5$: There is a positive relationship between variables.

Effect of Presence Over Creativity

A multiple regressions model was estimated to evaluate whether the scores in *embodiment, total presence*, and *overall perceived presence* could predict *creativity* (CPSS). The linear relationship between *embodiment, total presence*, *overall perceived presence,* and *creativity* was not statistically significant, $F(2,65) = 1.36$, $p = .26$. Outliers and influentials were accounted for: ZRESID, SRESID, SDRESID, Cook's Beta, DFBETA, and DFBETAS. Tests of homogeneity of variances and normality of residuals were conducted.

After analysis, null hypothesis H6 was retained. *Creativity* was not affected by *embodiment, total presence,* and *overall perceived presence.*

$H_0 6$: There is no relationship between variables.

$H_1 6$: There is a positive relationship between variables.

The Effect of CL on Spatial Abilities and Creativity

The objective of this section is to analyze the effect of presence on spatial abilities. The study investigated the following research questions using the NASA-TLX questionnaire, as well as an MRT and CPSS.

RQ3.1: How does cognitive load affect the development of spatial abilities?

RQ3.2: How does the cognitive load affect the creativity of the designed outcome in the design process?

- H7: The demand of cognitive load in immersive VR environments affects the development of spatial abilities.
- H8: The demand of cognitive load in immersive VR environments affects creativity in the design process.

Effect of CL Over Spatial Abilities

A multiple regressions model was estimated to evaluate whether the scores in *NASA-TLX* and *task difficulty* could predict *spatial abilities* (MRT). The linear relationship between *NASA-TLX*, *task difficulty*, and *spatial abilities* was not statistically significant, $F(2,69) = .451$, $p = .63$. Outliers and influentials were accounted for: ZRESID, SRESID, SDRESID, Cook's Beta, DFBETA, and DFBETAS. Tests of homogeneity of variances and normality of residuals were conducted.

After analysis, null hypotheses H7 was retained. *Spatial ability* was not affected by *CL*.

H_07: There is no relationship between variables.

H_17: There is a negative relationship between variables.

Effect of CL Over Creativity

A multiple regressions model was estimated to evaluate whether the scores in *NASA-TLX* and *task difficulty* could predict *creativity*. The linear relationship between *NASA-TLX*, *task difficulty*, and *creativity* (CPSS) was not statistically significant, $F(2,69) = .511$, $p = .60$. Outliers and influentials were accounted for: ZRESID, SRESID, SDRESID, Cook's Beta, DFBETA, and DFBETAS. Tests of homogeneity of variances and normality of residuals were conducted.

After analysis null hypotheses H8, was retained. *Creativity* was not affected by *CL*.

H_08: There is no relationship between variables.

H_18: There is a negative relationship between variables.

Additional Analysis

Aiming to better discern whether the VR intervention somehow affected the creative process, a multiple regressions model was estimated to evaluate whether the scores in self-perceived creativity (CPS) could predict creativity of the outcome (CPSS). The linear relationship between *NASA-TLX*, *task difficulty,* and *creativity* was not statistically significant, $F(1,70) = 1.91$, $p = .16$. Outliers and influentials were accounted for: ZRESID, SRESID, SDRESID, Cook's Beta, DFBETA, and DFBETAS. Tests of homogeneity of variances and normality of residuals were conducted.

Further analysis was conducted isolating the three conditions to see whether any affected the correlations between self-perceived creativity (CPS), and *creativity of the outcome* (CPSS). Multiple regressions models were estimated without statistical significance for Condition-1, Condition-2, and Condition-3, $F(1,22) = .41$, $p = .52$; $F(1,22) = 1.26$, $p = .27$; and $F(1,22) = .15$, $t = .70$. Outliers and influentials were accounted for: ZRESID, SRESID, SDRESID, Cook's Beta, DFBETA, and DFBETAS. Tests of homogeneity of variances and normality of residuals were conducted.

CHAPTER V

DISCUSSION AND CONCLUSIONS

In this study, one overarching research question was investigated: How does the sense of embodiment (SoE) through the virtual body (VB) affect ideation in the creative design process? Hypotheses H1 through H10 were tested. The objective of this section is to answer this question and all the derived sub-questions.

Analysis and Discussion

The Effect of VB on Presence and CL

RQ1.1: How does the VB affect the sense of presence? Results from the presence questions included in the post-experiment questionnaire support that different VB conditions affect the sense of presence. Only *appearance* had statistical significance between conditions from the four dimensions of presence measured (presence, appearance, interaction, and embodiment). This finding suggests that all environments gave participants the feeling of "being there." Nonetheless, the *appearance* dimension in Condition-3 obtained lower scores and was statistically significantly different from the other two conditions. This finding can be explained by the concepts of *place illusion* and *plausibility* (Slater, Spanlang, & Corominas, 2010). All the conditions generated the illusion of place, but interacting through an outside-of-body experience may have diminished the plausibility of the interaction's appearance. Also, first-person perspectives have more robust capabilities of generating body transfer illusions (Slater et al., 2010). Finally, the appearance between conditions may have affected the SoE, more specifically location and agency. It is important to recall that SoE is composed of three subcomponents: the sense of self-location, the sense of agency, and the sense of body ownership (Carruthers, 2013; Kilteni et al., 2012; Slater et al., 2010). *Appearance* refers to visual features; hence, Condition-3 mainly affected the senses of location and agency.

Because the designed interaction was mainly focused on thin operations while arranging the modules in the VR space, this study posited that the VB could affect interaction differently between conditions. This belief was supported by the fact that Condition-3 used a third-person perspective VB most used for displacement actions, whereas the first-person perspective is more appropriate for thin operations (Salamin et al., 2006). Nonetheless, no statistical difference was found in terms of *interaction* that could support that thought. Regardless of the perspective view of the VB, first- and third-person views equally supported the *interaction* dimension of presence.

The *overall appraisal of presence* was also of critical importance for this study. When participants were asked about their sense of presence, Condition-3 displayed statistical significance with Condition-1. Participants manifested higher appraisal of presence in Condition-1 than in the other two conditions. This is supported by the notion that the more an individual feels immersed in a virtual environment, the more they will behave according to that environment (Slater & Wilbur, 1997). The capacity of participants to see an online VB avatar in place of their own, from a first-person point of view, may have generated higher sensations of being inside the environment.

It is relevant to acknowledge that embodiment scores were consistent with the three conditions with no statistically significant differences. This finding is critical because this study hypothesized that embodied environments aid individuals to feel they are present in VR, and such was the case.

RQ1.2: How does the VB affect the cognitive load? Results from the NASA-TLX questions included in the post-experiment questionnaire supported a statistical difference for CL between conditions. Of the three conditions, Condition-2 was the one that had the lowest level of CL, and it had a statistically significant difference with Condition-3. No statistically significant differences were found between Condition-1 and Condition-2. These differences obtained from the NASA-TLX were consistent with the data captured with the fNIR device. Nonetheless, no statistical significance was obtained when contrasting the fNIR optodes' data between conditions. Overall, Condition-3 reported the highest amount of CL, followed by Condition-1 and Condition-2 in both NASA-TLX and fNIR data. This finding suggests that using online representations of the VB rather than reducing CL may positively affect the *extrinsic cognitive load*. It is important to recall that working memory is limited, and CL must be allocated among the three different types of CL (Sweller et al., 1998).

It is essential to remember that this study used fNIR data to support and expand on the CL data collected through the NASA-TLX. The fNIR data aimed not to discern between the activation of different brain regions or activation patterns. The right hemisphere has been traditionally linked to creative tasks, including spatial visualizations (MacNeilage et al., 2009). Nonetheless, this tendency to lateralize the brain between left and right hemispheres has been debated, and more unifying theories of the brain working collectively have arisen (Nielsen et al., 2013). From inspection of the fNIR data (bar graphs and brain topography), it appears that all three conditions had complete brain activation between left and right hemispheres. Only Condition-2 displayed a slight tendency to activate the right hemisphere. Beyond the activation of different brain regions, fNIR revealed insights into cognitive demand in the spatiotemporal factor. Analyzing the intervention in contrast to the variable of time, the condition that required more time for participants to complete the task was Condition-3, followed by Condition-1 and Condition-2.

Moreover, when optode activity was analyzed throughout the intervention, Condition-1 was the only condition in which cognitive demand increased in all optodes. Condition-3 displayed increasing cognitive demand in 12 of the 16 optodes, whereas in Condition-2, only nine of the 16 optodes increased. This finding may suggest that visualizing a VB can increase cognitive demand in time, similar to that proposed by Winograd and Flores (1986) when they discussed the concepts of ready-to-hand and present-at-hand. It seems that having a VB that aims to be an extension of the individual's body in VR ends up being an increasing cognitive factor of which the individual must be aware. Once again, this discussion points out that a VB helps increase the extraneous cognitive load in VR environments.

Moreover, when looking solely at *task difficulty* perceived by participants, no statistically significant differences were found. This finding suggests that the overall perception of the task's complexity was unified between conditions (*intrinsic cognitive load*). When comparing Condition-1 and Condition-2, the only difference between these two conditions was the inclusion of the online representation of the VB for the former, in contrast to the offline representation for the latter. This finding supports once more the inference that the inclusion of an online VB avatar for Condition-1 may have increased the *extrinsic cognitive load*. Because CL is limited and must be allocated mostly between *extraneous* and *germane* if *intrinsic* remains stable (Sweller et al., 1998), using an online VB can increase the overall presence—as discussed earlier with Condition-1, but to the detriment of cognition due to working memory limitations.

The Effect of VB on Spatial Ability

RQ1.3: How does the VB affect the development of spatial abilities? The comparison of first and second halves of MRT in the pre- and post-experiment questionnaires supports the hypothesis that immersive VR interactions can positively affect spatial abilities. The complete sample ($N = 72$) had statistical significance between pre- and post-experiment MRTs. This finding supports the notion that even short interaction in immersive VR can affect the neuroplasticity of participants (e.g., Cheung et al., 2014; Coco-Martin et al., 2020; Levin, 2011). Nonetheless, when looking at conditions independently, statistically significant differences were only found between Condition-1 and Condition-2.

The finding that VR can positively affect spatial abilities is critical to design education based on the theory of multiple intelligences proposed by Gardner (1983) and later revised by D'Souza (2006). Moreover, spatial ability has a crucial role in STEM instruction and development, and multiple studies have acknowledged the relationship between spatial skills and performance (Uttal & Cohen, 2012).

The Effect of VB on Creativity

RQ1.4: How does the VB affect creativity of the outcome? Rather than measuring creativity within the process, this study proposed to measure the creativeness of a designed outcome as an indicator of creativity among the three conditions. The pre-experiment questionnaire included the CPS, which supported no statistically significant differences in participants' self-perceived creativity between conditions. Later analysis used the CPSS embedded in the post-experiment questionnaire to assess the creativity of the designed outcome. Although there were no significant differences between conditions in the overall scores of the CPSS, when the three dimensions of *novelty*, *resolution*, and *elaboration and synthesis* were considered independently, statistical significance was found for *elaboration and synthesis*. Further analysis elicited that this difference was mainly between Condition-3 and Condition-1, in which the former had the lowest scores and the latter had the highest. This finding can be explained by the fact that third-person perspective is most used for displacement actions, whereas first-person perspective is more appropriate for thin operations (Salamin et al., 2006). This finding suggests that interactions developed to work as design environments should use first-person perspectives from a design process standpoint. This argument is based on the notion that design actions rely upon thin manual operations rather than bodily movements.

Beyond the differences in creativity of the outcomes among conditions, results show that Condition-2 displayed the lowest levels of CL of the three and the lowest levels of creativity. This finding elicits a new question: Could the lower level of creativity in

Condition-2 have been generated by not assigning the available working memory to *germane cognitive load*? Germane cognitive load is destined to create schemas in the working memory (Renkl & Atkinson, 2003; Sweller et al., 1998), and specifically in this study to propose a creative sculpture-like outcome. This new idea is supported by the previously discussed finding that not having an online VB in VR environments may reduce *extrinsic cognitive load,* which can be allocated to *intrinsic* or *germane cognitive load*. Moreover, it was previously supported that *intrinsic cognitive load* was similar throughout conditions. Hence, Condition-2 had the theoretical potential to have been more creative than the other two conditions, yet this was not the case. These arguments move the discussion further given that this study previously acknowledged the importance of engagement as a critical aspect of flow (Csikszentmihalyi & Nakamura, 2014). It is possible that not having an online VB negatively affected engagement, ultimately affecting flow in the creative process.

The Effect of Presence on Spatial Abilities and Creativity

RQ2.1: How does presence affect the development of spatial abilities? Data analysis from the presence questions included in the post-experiment questionnaire, correlated with the scores of the post-experiment MRT, displayed linear, positive statistical significance. This finding supports the notion that presence can help to improve spatial abilities in participants to a certain degree. It is important to emphasize that two models were run. The first model included the complete data of the sample, whereas the second eliminated outliers. No influencers were eliminated from any of the regression models.

This finding is coherent with that hypothesized in this study. As previously discussed, all conditions affected the sense of presence in participants. Moreover, participants felt they were embodied in the virtual space; previous research suggested that embodiment improves cognitive processes (Chu & Kita, 2011; DeSutter & Stieff, 2017; Poulsen & Thøgersen, 2011). Thus, engaging in scaffolded activities within immersive VR environments with a high sense of presence and embodiment helps improve spatial abilities. A *scaffold* is explained by Anderson (2003) with the definition used in cognitive sciences, which describes it as when an epistemic action constitutes a cognitive aid. Therefore, the activities need to be consistent with the cognitive interest of developing spatial abilities. Not every activity in immersive VR can help improve spatial skills.

RQ2.2: How does the sense of presence affect the creativity of the designed outcome in the design process? This study hypothesized that higher levels of presence could improve creative thinking. This was based on the fact that cognitive load can be released in the environment (Wilson, 2002). Removing cognitive load will liberate space in the working memory allocated to resolve the task at hand, therefore generating better solutions. Nonetheless, this was not the case in this study. When analyzing the presence data from the post-experiment questionnaire and the scores externally assigned to the outcomes, there was no relationship between variables.

A reason for this may be that this study used external evaluators to assess the level of creativeness of the designed outcome. This decision was based on the argument that creativity does not rely on the individual's mind engaging in creative thinking but on the viewer's perception of the outcome (Csikszentmihalyi, 1999). Consequently, the measure of creativity selected did not rely on the individual performing the task but rather on the perception of the viewers.

The Effect of CL on Spatial Abilities and Creativity

RQ3.1: How does CL affect the development of spatial abilities? When data from NASA-TLX questions of the post-experiment questionnaire were analyzed in relation to spatial abilities, no statistically significant results were found. Nonetheless, as previously discussed, this study supported that the immersive VR intervention improved spatial abilities. No correlation was found between CL and spatial abilities because instruments to measure CL cannot discern between the three subcomponents of CL (intrinsic, extrinsic, and germane). Therefore, it is impossible to analyze whether liberated CL was indeed assigned to the cognition of spatial skills or any other experimental aspect. This finding opens interesting possibilities for future research in which qualitative data or protocol analysis could help to better understand the individual's thinking process while performing a task.

And *RQ3.2: How does the CL affect the creativity of the designed outcome in the design process?* Once again, this study hypothesized that released CL could have been allocated to better cater to the design problem and yield a more creative outcome. As previously discussed, the instrument selected to measure creativity relied on the perception of external viewers rather than on the participant. Hence, no relationship whatsoever between CL and the creativity of the outcome was found.

Due to that, the creativity of the outcome was not explained by presence or CL; further analysis was done by correlating the CPS from the pre-experiment questionnaire with the CPSS scores. No relationship whatsoever was found between these two instruments. It was interesting to observe that individuals perceived themselves as creative, but their outcomes were not recognized as so. This argument aligns with the posture of Csikszentmihalyi (1999) that a crucial factor of creativity depends on society and those gatekeepers that allow outcomes to access the domain.

Conclusions

The main research question of this study focused on the effect of the VB over idea generation in the creative design process. Its purpose was to evaluate the use of high embodiment digital tools, more specifically immersive VR, as a positive influencer for idea generation and spatial ability development. The central hypothesis portrayed that different VB could affect the SoE, positively affecting the presence and reducing cognitive load while increasing spatial ability and creativity.

Seventy-two individuals participated in an experiment in which they were required to manipulate modular cubes inside an IVR environment. Participants were randomly assigned to one of three conditions. Pre- and post-experiment questionnaires were used to capture data regarding demographics, self-perceived creativity, cognitive load, and presence. A psychophysiological device was used to expand cognitive load data interpretation. Also, a rubric was used to evaluate the creativity of the designed outcome by three independent scorers. Data were statistically analyzed and discussed to generate conclusions regarding the influence of the VB over presence, CL, spatial ability, and creativity.

The first important finding was that participants felt present among all VB conditions inside the IVR environments. As previously discussed, when individuals feel they are present in an environment, they will behave accordingly, and the SoE will permit embodied actions. Nonetheless, this study demonstrates that it is critical to understand the type of activities (action movements or thin operations) individuals will perform inside these environments to select the ideal VB condition. A wrong selection of a VB representation may negatively affect presence. Furthermore, the correct selection of the virtual environment can affect engagement in the proposed activity, which ultimately will affect the *flow*.

Second, this study showed that CL could diminish in immersive VR environments when the VB is manipulated. The VB must be carefully controlled because even though it can increase the sensation of presence in individuals, it can negatively affect task performance due to extraneous information that increases CL. Also, this study explored the evolution of CL in the time dimension of the intervention. This aspect is of critical relevance because previous psychometric tools to measure CL only allow capture of data at one specific moment. By using fNIRs, data can be analyzed throughout the time dimension to better understand the evolution of CL during the intervention.

Third, scaffolded activities in immersive VR environments can positively affect the development of spatial abilities. This study showed that even a short intervention in VR in which individuals are required to manipulate spatial objects and navigate inside a space positively affects spatial skills. This finding is critical for design and STEM education, in which spatial skills are deemed highly important. Moreover, this conclusion suggests that similar setups can be used across disciplines other than design to increase spatial ability.

Fourth, creativity is a subjective construct. Even though multiple instruments exist to assess creativity, such as self-report questionnaires or rubrics to evaluate the creative outcome, the creative thinking process remains a topic open to exploration and research. This study was not able to conclusively support the idea that more embodied IVR environments stimulated creative thinking. Nonetheless, all conditions permitted idea generation, novel designed outcomes, and a broad spectrum of different resolution, elaboration, and synthesis levels. This conclusion is of high relevance to the design discipline because it opens the possibility to use IVR environments as ideation platforms to approach different stages of the design process.

Furthermore, this study meant to diminish the gap on the positive influence of digital media tools in ideation practices at the conceptual design stage. To do so, it focused on answering one overarching research question: *How does the Sense of Embodiment (SoE) through the Virtual Body (VB) affect ideation in the creative design process?* Through analysis and discussion, it was supported that different uses of the VB affect presence and CL. Moreover, immersive VR environments permit idea generation, yield novel outcomes, but above all, can improve spatial abilities on individuals. This last element is a critical component of design education (Allen, 2010; Cho, 2017; Zacks et al., 2000).

Implications

The results of this study offer multiple implications from theoretical, methodological, and practical standpoints. These implications will provide insights to researchers, designers, and design educators on how the VB in IVR environments can be manipulated according to their specific interests. Furthermore, the findings of this study offer information to developers of instructional media using IVR environments.

Theoretical Implications

From a theoretical standpoint, this study bridges cognitive psychology, design theory, and computational sciences to explain the effect of different VBs on the creative design process. Moreover, this study used IVR as an emerging design tool to elicit creativity within the design process. This is a novel approach given that previous research has seen digital media tools as restrictive to ideation stages of the design process; nonetheless, the value of iterating between media has been acknowledged.

First, findings suggest that variations in VB type and iterations between online and offline representations have repercussions in CL demand. Working memory is limited, and the way the VB is represented within VR environments may affect *extraneous cognitive load* by providing unnecessary information to the users. According to CLT, if the *intrinsic cognitive load* is constant, resources destined to tackle *extraneous cognitive load* will diminish *germane cognitive load* destined to build schemas. Ultimately, these redistributions between the diverse types of CL will affect the expected learning outcome.

Second, the design process has been researched through different lenses trying to better understand how creativity unfolds within it. Findings suggest that there is no relationship between the self-reported creativity of individuals and the creativeness of their outcomes. Even though this study did not evaluate the design process, it supported the notion that IVR environments have the capacity to elicit idea generation. Beyond idea generation, these environments support the sensation of presence and embodiment. These two attributes are relevant for the design process given that embodied actions help cognitive functions such as spatial knowledge. In addition, this study expanded on design theory despite the fact that digital media tools have been seen as restrictive for ideation, but changing media can increase creative outcomes. IVR environments can be used as design manipulation tools to explore different perspectives of a design project throughout the design process. These manipulations can aid in developing new innovative ideas.

Third, this study provides empirical data on the differences between online and offline representations of the VB from a computational sciences standpoint. Furthermore, it provides information on how third-person and first-person VB points of view can affect individuals beyond the performance of action movements or thin operations.

Methodological Implications

Physiological tools open a window to design research that has been scarcely explored in the past. This study combined the characteristics of fNIR and psychometric measures to deepen the understanding of cognitive demand in a specific task. Moreover, the use of fNIR as a psychophysiological tool permitted the exploration of CL variations throughout the task. This is remarkable because psychometric tools only give researchers insight on CL at one specific moment after the intervention.

Also, this study explored the feasibility of manipulating IVR environments to stimulate idea generation through embodied actions. IVR was backed as an effective tool to research controlled environments. This study demonstrated how different variables such as VB, point of view, or appearance can be intentionally manipulated or monitored according to the research scope.

Practical Implications

From a practical standpoint, the findings of this study contribute to help designers and design educators develop IVR environments. The results suggest that selecting an appropriate VB for the required VR environment is critical for presence and cognitive load. Online representations of the VB may increase the sensation of being present, but they ultimately can create distracting information that negatively affects cognitive load. Besides, it is very important to properly select the type of online representation in accordance with the expected activities (action movements or thin operations). Offline representations, on the contrary, do not generate much deeper sensations of presence but also do not contribute unnecessary information to individuals that may affect their cognitive processes.

VR can be a powerful tool for design instruction. Findings support that manipulating objects in virtual spaces and moving within these spaces positively affects spatial abilities development. Previous research has shown that video games can enhance spatial skills (Wu et al., 2012). This study reinforced this idea and supported the fact that short interventions of about 20 min in VR using embodied actions can do that as well. Furthermore, this study supports the notion that digital tools can go beyond being considered solely as visualization tools. If properly manipulated, VR environments can generate scenarios with enough ambiguity to elicit emergence. Even though no statistical significance was achieved when the variables were compared with creativity, in the outcome evaluation, multiple outcomes were scored highly.

Limitations

The current study was designed and deliberately selected valid and reliable instruments for data collection. In addition, the VR intervention was designed to control for external variables that isolated the independent variable (VB) as much as possible.

Nonetheless, as in all research of an experimental nature, some inescapable limitations were present.

First, this study used a convenience sample of undergraduate and graduate students of a midwestern university in the United States. To achieve statistical power and a large sample size, not all participants were from design-related fields. This was not considered a constraint because the study chose instruments to assess the creativity of the outcome and self-reported creativity, not of the design process. All the participants were from the same campus and probably lived in the same region with very similar cultural influences. Furthermore, the participants were not evenly distributed in gender classification; most of the sample were females between 18 and 24 years old.

The second limitation was the interaction between the fNIR device and the VR HMD. The fNIR must be placed on the forehead of participants, and the external light must be controlled so it cannot affect the internal readings. The VR HMD was placed above the fNIR headband. This condition sometimes permitted the light of the HMD to enter the lower central optodes of the fNIR device (OP6, OP8, OP10, OP12). These data were later cleaned using the filtering process, but data loss for these specific optodes is a possibility.

The third limitation was the physical space for the experiment. Due to space constraints and wiring requirements for the fNIR device, individuals were required to teleport from point to point using the hand controls. This condition may have prevented individuals from having greater levels of presence or eliciting more embodiment.

Finally, this study's major limitation was that the data collection occurred during the Coronavirus 2019 (CoViD-19) pandemic. This negatively impacted the timeline for data collection, as the study data collection took one year to complete. In addition, the participants were required to wear masks while using the HMD, which might have generated discomfort.

Future Directions

The current study presents multiple possibilities for further inquiry aiming to better understand the impact of digital media in stimulating creativity and improving the design process or design teaching practices. Moreover, it emphasized the use of novel methodologies for design research in the realms of cognitive science. Above all, this study explored novel digital media tools that were exclusive, expensive, and underdeveloped in the past. VR is a large market that is gaining acceptance daily by consumers, researchers, and developers who realize the potential of ubiquitous presence. New VR headsets are starting to rely in inside-out technology that makes them wireless. This opens possibilities for new research in embodied actions easily. In addition, physiological tools are also moving into wireless domains.

First, the current study provides empirical evidence of the positive influence of interaction in VR environments for developing spatial abilities. Further studies could discriminate the types of embodied actions and spatial characteristics to better understand the influence of these on spatial skills. As previously discussed, it seems that even short VR interactions can affect plasticity in the brain. A longitudinal approach could be used to research the perpetuity of the developed spatial skills over time. This approach can open the opportunity to develop curricular strategies on design education throughout the learning process. Furthermore, it may yield strategies in which different interventions offered to design students in distinct levels could improve their spatial skills.

Second, the methodology and setup of this study can be replicated with greater emphasis on researching how the multiple conditions affected the number of generated ideas within the design process beyond assessing the creativity of the outcome. Protocol analysis is a technique that has been used since the ’90s to research the design process through verbalization (e.g., Suwa et al., 1998). This technique could provide interesting insights to better understand what happens in the designer’s mind when interacting in the VR environment. In addition, using linkography (Goldschmidt, 1990), the proposed ideas can be quantified to better understand the differences between conditions.

Third, the different VBs supported benefits either for displacement actions or thin operations. Future studies can discern between the effects of these actions on the development of spatial skills and creative thinking. Because the advantages of each type of VB have been supported depending on the specific action to perform, the question arises: What will happen if individuals could shift at will between multiple points of view? Previous research has supported the idea that shifting between media can improve creativity (Shih et al., 2015, 2017); similarly, moving between VB could help to improve spatial skills and creativity.

Fourth, this study could be replicated using a different immersive digital media tool that enables embodied actions. A good example is augmented reality (AR) because it can use embodied actions to manipulate virtual objects that are juxtaposed in the natural environment. The methodology of this study could be replicated using different conditions or manipulation styles within AR.

Finally, this study combined psychophysiological and psychometric tools to assess idea development in the design process. This is a novel approach that is open to adaptation and replication in different activities similar to the creative process. Moreover, the research conducted in this study is expected to contribute to the design discipline in developing technology-based pedagogical strategies for design education.

REFERENCES

Ahn, S. J. G., Bailenson, J. N., & Park, D. (2014). Short-and long-term effects of embodied experiences in immersive virtual environments on environmental locus of control and behavior. *Computers in Human Behavior*, *39*, 235–245.

Alias, M., Black, T. R., & Gray, D. E. (2002). Effect of instruction on spatial visualization ability in civil engineering students. *International Education Journal*, *3*(1), 1–12.

Alibali, M. W., & Nathan, M. J. (2012). Embodiment in mathematics teaching and learning: Evidence from learners' and teachers' gestures. *Journal of the Learning Sciences*, *21*(2), 247–286.

Allahyar, M., & Hunt, E. (2003). The assessment of spatial orientation using virtual reality techniques. *International Journal of Testing*, *3*(3), 263–275.

Allen, A. D. (2010). Complex spatial skills: The link between visualization and creativity. *Creativity Research Journal*, *22*(3), 241–249.

Anderson, M. L. (2003). Embodied cognition: A field guide. *Artificial Intelligence*, *149*(1), 91–130.

Archer, L. B. (1965). *Systematic Method for Designers.* Council of Industrial Design.

Ayres, P., & Sweller, J. (2005). The split-attention principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 135–146). Cambridge University Press.

Ayaz, H., Onaral, B., Izzetoglu, K., Shewokis, P. A., McKendrick, R., & Parasuraman, R. (2013). Continuous monitoring of brain dynamics with functional near infrared spectroscopy as a tool for neuroergonomic research: Empirical examples and a technological development. *Frontiers in Human Neuroscience*, *7*, 871.

Ayaz, H. (2010). *Functional near infrared spectroscopy based brain computer interface* [Unpublished doctoral thesis]. Drexel University.

Ayaz, H., Izzetoglu, M., Shewokis, P. A., & Onaral, B. (2010, August). Sliding-window motion artifact rejection for functional near-infrared spectroscopy. In *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology* (pp. 6567–6570). IEEE.

Baddeley, A. (1992). Working memory. *Science*, *255*(5044), 556–559.

Baer, J. (2010). Is creativity domain specific? In J. C. Kaufman & R. J. Sternberg (Eds.), *The Cambridge handbook of creativity* (pp. 321–341). Cambridge University Press.

Baren, J. V., & IJsselsteijn, W. (2004). *Measuring presence: A guide to current measurement approaches* [Project report]. OmniPres Project IST-2001-39237.

Baron, R. A., & Byrne, D. (1987). *Social psychology: Understanding human interaction*. Allyn & Bacon.

Bilda, Z., & Demirkan, H. J. D. (2003). An insight on designers' sketching activities in traditional versus digital media. *Design Studies 24*(1), 27–50.

Bijl, A. (1987). An approach to design theory. In H. Yoshikawa & E. Warman (Eds.), *Design theory in CAD* (pp. 3–25). North-Holland.

Biocca, F., Burgoon, J., Harms, C., & Stoner, M. (2001, May 21–23). *Criteria and scope conditions for a theory and measure of social presence* (Paper presentation]. Presence 2001, 4th Annual International Workshop, Philadelphia, PA, United States.

Biocca, F., Harms, C., & Burgoon, J. K. (2003). Toward a more robust theory and measure of social presence: Review and suggested criteria. *Presence: Teleoperators & Virtual Environments*, *12*(5), 456–480.

Bosnyak, A., & Nagy-Kondor, R. (2008). The spatial ability and spatial geometrical knowledge of university students majored in mathematics. *Acta Didactica Universitatis Comenianae*, *8*, 1–25.

Bric, J., Connolly, M., Kastenmeier, A., Goldblatt, M., & Gould, J. C. (2014). Proficiency training on a virtual reality robotic surgical skills curriculum. *Surgical Endoscopy*, *28*(12), 3343–3348.

Brown, A., & Green, T. (2016). Virtual reality: Low-cost tools and resources for the classroom. *TechTrends*, *60*(5), 517–519.

Burnett, S. A., & Lane, D. M. (1980). Effects of academic instruction on spatial visualization. *Intelligence*, *4*(3), 233–242.

Burnett, S. A., Lane, D. M., & Dratt, L. M. (1979). Spatial visualization and sex differences in quantitative ability. *Intelligence*, *3*(4), 345–354.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge University Press.

Carruthers, G. (2008). Types of body representation and the sense of embodiment. *Consciousness and Cognition*, *17*(4), 1302–1316.

Carruthers, G. (2013). Toward a cognitive model of the sense of embodiment in a (rubber) hand. *Journal of Consciousness Studies*, *20*(3–4), 33–60.

Chandrasekera, T. (2015). *The effect of augmented reality and virtual reality interfaces on epistemic actions and the creative process* [Unpublished doctoral dissertation], University of Missouri–Columbia. https://mospace.umsystem.edu/xmlui/bitstream/handle/10355/57754/research.pdf?sequence=2

Chandrasekera, T., & Yoon, S-Y. (2015). Adopting augmented reality in design communication. *The International Journal of Architectonic, Spatial, and Environmental Design*, *9*(1), 1–14. https://doi.org/10.18848/2325-1662/CGP/v09i01/38384

Chao, C. J., Wu, S. Y., Yau, Y. J., Feng, W. Y., & Tseng, F. Y. (2017). Effects of three-dimensional virtual reality and traditional training methods on mental workload and training performance. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *27*(4), 187–196.

Chao, L. L., & Martin, A. (2000). Representation of manipulable man-made objects in the dorsal stream. *Neuroimage*, *12*(4), 478–484.

Cheung, K. L., Tunik, E., Adamovich, S. V., & Boyd, L. A. (2014). Neuroplasticity and virtual reality. In *Virtual Reality for Physical and Motor Rehabilitation* (pp. 5–24). Springer.

Cho, J. Y. (2017). An investigation of design studio performance in relation to creativity, spatial ability, and visual cognitive style. *Thinking Skills and Creativity*, *23*, 67–78.

Christiaans, H. H. (2002). Creativity as a design criterion. *Communication Research Journal*, *14*(1), 41–54.

Chu, M., & Kita, S. (2011). The nature of gestures' beneficial role in spatial problem solving. *Journal of Experimental Psychology: General*, *140*(1), 102.

Clark, A. (1998). *Being there: Putting brain, body, and world together again*. MIT Press.

Coco-Martin, M. B., Piñero, D. P., Leal-Vega, L., Hernández-Rodríguez, C. J., Adiego, J., Molina-Martín, A., de Fez, D., & Arenillas, J. F. (2020). The potential of virtual reality for inducing neuroplasticity in children with amblyopia. *Journal of Ophthalmology*, *2020,* Article 7067846.

Collins, K. M., Onwuegbuzie, A. J., & Jiao, Q. G. (2007). A mixed methods investigation of mixed methods sampling designs in social and health science research. *Journal of Mixed Methods Research*, *1*(3), 267–294.

Coomans, M. K., & Timmermans, H. J. (1997). Towards a taxonomy of virtual reality user interfaces. In *Proceedings: 1997 IEEE Conference on Information Visualization* (Cat. No. 97TB100165; pp. 279–284). IEEE.

Creswell, J. W., & Clark, V. L. P. (2017). *Designing and conducting mixed methods research*. Sage Publications.

Cross, N. (1982). Designerly ways of knowing. *Design Studies 3*(4), 221–227.

Cross, N. (1990). The nature and nurture of design ability. *Design Studies 11*(3), 127–140.

Csikszentmihalyi, M. (1998). Letters from the field. *Roeper Review*, *21*(1), 80–81.

Csikszentmihalyi, M. (1999). 16 implications of a systems perspective for the study of creativity. *Handbook of creativity* (pp. 313–336). Cambridge University Press.

Csikszentmihalyi, M., Abuhamdeh, S., & Nakamura, J. (2014). Flow. In *Flow and the foundations of positive psychology* (pp. 227–238). Springer.

Darke, J. (1979). The primary generator and the design process. *Design Studies 1*(1), 36–44.

Darken, R. P., Allard, T., & Achille, L. B. (1998). Spatial orientation and wayfinding in large-scale virtual spaces: An introduction. *Presence*, *7*(2), 101–107.

Dayan, E., & Cohen, L. G. (2011). Neuroplasticity subserving motor skill learning. *Neuron*, *72*(3), 443–454.

Demirkan, H., & Afacan, Y. (2012). Assessing creativity in design education: Analysis of creativity factors in the first-year design studio. *Design Studies*, *33*(3), 262–278.

DeSutter, D., & Stieff, M. (2017). Teaching students to think spatially through embodied actions: Design principles for learning environments in science, technology, engineering, and mathematics. *Cognitive Research: Principles and Implications*, *2*(1), Article 22.

Dourish, P. (2001). *Where the action is*. MIT Press.

Dreyfus, H. L. (1996). The current relevance of Merleau-Ponty's phenomenology of embodiment. *The Electronic Journal of Analytic Philosophy*, *4*(4), 1–16.

D'Souza, N. S. (2006). *Design intelligences: A case for multiple intelligences in Architectural Design* (Publication No. 304984974) [Doctoral dissertation, University of Wisconsin–Milwaukee]. ProQuest Dissertations & Theses Global. http://argo.library.okstate.edu/login?url=https://www.proquest.com/docview/304984974?accountid=4117

Etemad-Sajadi, R. (2016). The impact of online real-time interactivity on patronage intention: The use of avatars. *Computers in Human Behavior*, *61*, 227–232.

Feist, G. J. (2004). The evolved fluid specificity of human creative talent. In R. J. Sternberg, E. L. Grigorenko, & J. L. Singer (Eds.), *Creativity: From potential to realization* (pp. 57–82). American Psychological Association.

Ferrari, M., & Quaresima, V. (2012). A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *Neuroimage*, *63*(2), 921–935.

Franklin, N., & Tversky, B. (1990). Searching imagined environments. *Journal of Experimental Psychology: General*, *119*(1), 63–76.

Gall, M. D., Gall, J. P., & Borg, W. R. (2007). Collecting research data with questionnaires and interviews. *Educational Research: An Introduction*, *12*(10), 227–261.

Galvan Debarba, H., Bovet, S., Salomon, R., Blanke, O., Herbelin, B., & Boulic, R. (2017). Characterizing first and third person viewpoints and their alternation for embodied interaction in virtual reality. *PLoS One*, *12*(12), Article e0190109.

Ganis, G., Thompson, W. L., & Kosslyn, S. M. (2004). Brain areas underlying visual mental imagery and visual perception: An fMRI study. *Cognitive Brain Research*, *20*(2), 226–241.

Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences*. Basic Books.

Gericke, K., & Blessing, L. (2011). Comparisons of design methodologies and process models across domains: A literature review. In *DS 68-1: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society Through Engineering Design: Vol. 1. Design Processes, Lyngby/Copenhagen, Denmark, 15.-19.08.2011* (pp. 393–404).

Gerry, L. J. (2017). Paint with me: Stimulating creativity and empathy while painting with a painter in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, *23*(4), 1418–1426.

Goffman, E. (2002). *The presentation of self in everyday life*. (Original work published 1959) *259*.

Goldschmidt, G. (1990, April 17–20). *Linkography: assessing design productivity* [Paper presentation]. Cybernetics and System '90, Proceedings of the Tenth European Meeting on Cybernetics and Systems Research, Vienna, Austria.

Goldschmidt, G. (1991). The dialectics of sketching. *Creativity Research Journal*, *4*(2), 123–143.

Gough, H. G. (1979). A creative personality scale for the adjective check list. *Journal of Personality and Social Psychology*, *37*(8), 1398–1405.

Gough, H. G. (1992). Assessment of creative potential in psychology and the development of a creative temperament scale for the CPI. In J. C. Rosen & P. McReynolds (Eds.), *Advances in psychological assessment* (pp. 225–257). Springer.

Guilford, J. (1950). Creativity. *American Psychologist*, *5*(9), 444–454.

Guilford, J. P., & Hoepfner, R. (1971). *The analysis of intelligence* (pp. 169–170). McGraw-Hill.

Hannah, G. G. (2002). *Elements of design: Rowena Reed Kostellow and the structure of visual relationships*. Princeton Architectural Press.

Hart, S. G. (2006). NASA-Task Load Index (NASA-TLX); 20 years later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *50*, 904–908.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in Psychology*, *52*, 139–183.

Heldal, I., Roberts, D., Bråthe, L., & Wolff, R. (2007, July). Presence, creativity and collaborative work in virtual environments. In J. A. Jacko (Ed.), *International Conference on Human-Computer Interaction* (pp. 802–811). Springer.

Henning, P. H. (2004). Everyday cognition and situated learning. In D. H. Jonassen (Ed.), *Handbook of research on educational communications and technology: A project of the Association for Educational Communications and Technology* (pp. 829–861). Routledge.

Hernandez, C. R. B. (2006). Thinking parametric design: Introducing parametric Gaudi. *Design Studies*, *27*(3), 309–324.

Hilditch, D. J. (1997). *At the heart of the world: Merleau-Ponty and the existential phenomenology of embodied and embedded intelligence in everyday coping* (Publication No. 304247150) [Doctoral dissertation, Washington University]. ProQuest Dissertations & Theses Global. http://argo.library.okstate.edu/login?url=https://www.proquest.com/docview/304247150?accountid=4117

Hocevar, D. (1981). Measurement of creativity: Review and critique. *Journal of Personality Assessment*, *45*(5), 450–464.

Hoonakker, P., Carayon, P., Gurses, A. P., Brown, R., Khunlertkit, A., McGuire, K., & Walker, J. M. (2011). Measuring workload of ICU nurses with a questionnaire survey: The NASA Task Load Index (TLX). *IIE Transactions on Healthcare Systems Engineering*, *1*(2), 131–143.

Hopfenblatt, J., & Balakrishnan, B. (2018, May 17–19). The "Nine-Square Grid" revisited: 9-cube VR—An exploratory virtual reality instruction tool for foundation studios. In T. Fukuda, W. Huang, P. Janssen, K. Crolla, & S. Alhadidi (Eds.), *Learning, adapting and prototyping—Proceedings of the 23rd annual conference of the Computer Aided Architectural Design Research in Asia, Tsinghua University, Beijing, China* (Vol. 1, pp. 463–471). http://papers.cumincad.org/cgi-bin/works/Show?caadria2018_066

Hudelot, C., Atif, J., & Bloch, I. (2008). Fuzzy spatial relation ontology for image interpretation. *Fuzzy Sets and Systems*, *159*(15), 1929–1951.

Ibrahim, R., & Rahimian, F. P. (2010). Comparison of CAD and manual sketching tools for teaching architectural design. *Automation in Construction*, *19*(8), 978–987.

International Society for Presence Research. (2000). The concept of presence: Explication statement. https://ispr.info/about-presence-2/about-presence/

Izzetoglu, K., Ayaz, H., Merzagora, A., Izzetoglu, M., Shewokis, P. A., Bunce, S. C., Pourrezaei, K., Rosen, A., & Onaral, B. (2011). The evolution of field deployable fNIR spectroscopy from bench to clinical settings. *Journal of Innovative Optical Health Sciences*, *4*(3), 239–250.

Johnson-Glenberg, M. C. (2018). Immersive VR and education: Embodied design principles that include gesture and hand controls. *Frontiers in Robotics and AI*, *5*, 81.

Jonson, B. (2005). Design ideation: The conceptual sketch in the digital age. *Design Studies*, *26*(6), 613–624.

Kaimal, G., Ayaz, H., Herres, J., Dieterich-Hartwell, R., Makwana, B., Kaiser, D. H., & Nasser, J. A. (2017). Functional near-infrared spectroscopy assessment of reward perception based on visual self-expression: Coloring, doodling, and free drawing. *The Arts in Psychotherapy*, *55*, 85–92.

Kalay, Y. E. (2004). *Architecture's new media: Principles, theories, and methods of computer-aided design*. MIT Press.

Kan, J. W., & Gero, J. S. (2008). Acquiring information from linkography in protocol studies of designing. *Design Studies*, *29*(4), 315–337.

Kaufman, J. C., & Baer, J. (2004). Sure, I'm creative—but not in mathematics! Self-reported creativity in diverse domains. *Empirical Studies of the Arts*, *22*(2), 143–155.

Kaufman, J. C., & Beghetto, R. A. (2009). Beyond big and little: The four C model of creativity. *Review of General Psychology*, *13*(1), 1–12.

Kaufman, J. C., Cole, J. C., & Baer, J. (2009). The construct of creativity: Structural model for self-reported creativity ratings. *The Journal of Creative Behavior*, *43*(2), 119–134.

Kell, H. J., Lubinski, D., Benbow, C. P., & Steiger, J. H. (2013). Creativity and technical innovation: Spatial ability's unique role. *Psychological Science*, *24*(9), 1831–1836.

Kenny, A. (1985). *The philosophical writings of Descartes* (Vol. 1). Cambridge University Press.

Keshner, E. A., & Kenyon, R. V. (2009). Postural and spatial orientation driven by virtual reality. *Studies in Health Technology and Informatics*, *145*, 209–228.

Kilteni, K., Groten, R., & Slater, M. (2012). The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments*, *21*(4), 373–387.

Kirsh, D., & Maglio, P. (1994). On distinguishing epistemic from pragmatic action. *Cognitive Science*, *18*(4), 513–549.

Kozhevnikov, M., Motes, M. A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science*, *31*(4), 549–579.

Kwon, J.-H., Choi, H.-W., Lee, J.-I., & Chai, Y.-H. (2005). Free-hand stroke based NURBS surface for sketching and deforming 3D contents. In Y. S. Ho & H. J. Kim (Eds.), *Advances in multimedia processing—PCM 2005. Lecture Notes in Computer Science* (Vol. 3767, pp. 315–326). Springer.

Leahy, W., & Sweller, J. (2004). Cognitive load and the imagination effect. *Applied Cognitive Psychology*, *18*(7), 857–875.

Lee, K. M. (2004). Presence, explicated. *Communication Theory*, *14*(1), 27–50.

Levin, M. F. (2011). Can virtual reality offer enriched environments for rehabilitation? *Expert Review of Neurotherapeutics*, *11*(2), 153–155.

Liao, S. C., Hunt, E. A., & Chen, W. (2010). Comparison between inter-rater reliability and inter-rater agreement in performance assessment. *Annals, Academy of Medicine Singapore*, *39*(8), 613.

Lin, H. (2016). Influence of design training and spatial solution strategies on spatial ability performance. *International Journal of Technology and Design Education*, *26*(1), 123–131.

Lin, H. C., Chang, Y. S., & Li, W. H. (2020). Effects of a virtual reality teaching application on engineering design creativity of boys and girls. *Thinking Skills and Creativity*, *37*, Article 100705.

Lin, M. (2016). *Boundaries*. Simon & Schuster.

Lobell, J. (1975). Design and the powerful logics of the mind's deep structures. *DMG-DRS Journal: Design Research and Methods, 9*(2), 122–129.

Lohman, D. F. (1996). Spatial ability and G. In I. Dennis & P. Tapsfield (Eds.), *Human abilities: Their nature and measurement* (97–116). Lawrence Erlbaum.

Lombard, M., Biocca, F., Freeman, J., IJsselsteijn, W., & Schaevitz, R. J. (Eds.). (2015). *Immersed in media: Telepresence theory, measurement & technology*. Springer.

Lombard, M., & Jones, M. T. (2015a). Defining presence. http://matthewlombard.com/presence-definitions/

Lombard, M., & Jones, M. T. (2015b). Defining presence. In M. Lombard, F. Biocca, W.A. IJsselsteijn, J. Freeman, & R. Schaevitz (Eds.), *Immersed in media: Telepresence theory, measurement and technology*. Springer.

Loomis, J. M. (1992). Distal attribution and presence. *Presence: Teleoperators & Virtual Environments*, *1*(1), 113–119.

MacNeilage, P. F., Rogers, L. J., & Vallortigara, G. (2009). Origins of the left & right brain. *Scientific American*, *301*(1), 60–67.

Maeda, Y., & Yoon, S. Y. (2013). A meta-analysis on gender differences in mental rotation ability measured by the Purdue spatial visualization tests: Visualization of rotations (PSVT: R). *Educational Psychology Review*, *25*(1), 69–94.

Mayer, R. E., & Sims, V. K. (1994). For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning. *Journal of Educational Psychology*, *86*(3), 389–401.

McGee, M. G. (1979). Human spatial abilities: Psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin*, *86*(5), 889–918.

McLellan, H. (1996). Virtual realities. *Handbook of research for educational communications and technology* (pp. 457–487). Macmillan.

Meniru, K., Rivard, H., & Bédard, C. (2003). Specifications for computer-aided conceptual building design. *Design Studies 24*(1), 51–71.

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, *77*(12), 1321–1329.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*(2), 81–97.

Minsky, M. (1980). Telepresence. *Omni*, pp. 45–51.

Mizell, D. W., Jones, S. P., Slater, M., & Spanlang, B. (2002). *Comparing immersive virtual reality with other display modes for visualizing complex 3D geometry*. University College London.

Morgan, D. L. (2007). Paradigms lost and pragmatism regained: Methodological implications of combining qualitative and quantitative methods. *Journal of Mixed Methods Research*, *1*(1), 48–76.

Nagy-Kondor, R. (2017). Spatial ability: Measurement and development. In M. S. Khine (ed.), *Visual-spatial ability in STEM education* (pp. 35–58). Springer.

Nielsen, J. A., Zielinski, B. A., Ferguson, M. A., Lainhart, J. E., & Anderson, J. S. (2013). An evaluation of the left-brain vs. right-brain hypothesis with resting state functional connectivity magnetic resonance imaging. *PloS One*, *8*(8), e71275.

Olkun, S. (2003). Making connections: Improving spatial abilities with engineering drawing activities. *International Journal of Mathematics Teaching and Learning*, *3*(1), 1–10.

Onwuegbuzie, A. J., & Johnson, R. B. (2006). The validity issue in mixed research. *Research in the Schools*, *13*(1), 48–63.

Oxman, R. (2002). The thinking eye: Visual re-cognition in design emergence. *Design Studies*, *23*(2), 135–164.

Paas, F. G., & Van Merriënboer, J. J. (1994a). Instructional control of cognitive load in the training of complex cognitive tasks. *Educational Psychology Review*, *6*(4), 351–371.

Paas, F. G., & Van Merriënboer, J. J. (1994b). Variability of worked examples and transfer of geometrical problem-solving skills: A cognitive-load approach. *Journal of Educational Psychology*, *86*(1), 122–133.

Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and instructional design: Recent developments. *Educational Psychologist*, *38*(1), 1–4.

Palmiero, M., & Srinivasan, N. (2015). Creativity and spatial ability: A critical evaluation. In J. A. Manjaly & B. Indurkhya (Eds.), *Cognition, Experience and Creativity* (pp. 189–214). Orient Blackswan.

Pellegrino, J. W., Alderton, D. L., & Shute, V. J. (1984). Understanding spatial ability. *Educational Psychologist*, *19*(4), 239–253.

Peters, M., & Battista, C. (2008). Applications of mental rotation figures of the Shepard and Metzler type and description of a mental rotation stimulus library. *Brain and Cognition*, *66*(3), 260–264.

Piffer, D. (2012). Can creativity be measured? An attempt to clarify the notion of creativity and general directions for future research. *Thinking Skills and Creativity*, *7*(3), 258–264.

Pouliquen-Lardy, L., Milleville-Pennel, I., Guillaume, F., & Mars, F. (2016). Remote collaboration in virtual reality: Asymmetrical effects of task distribution on spatial processing and mental workload. *Virtual Reality*, *20*(4), 213–220.

Poulsen, S. B., & Thøgersen, U. (2011). Embodied design thinking: A phenomenological perspective. *CoDesign*, *7*(1), 29–44.

Purcell, A. T., & Gero, J. S. (1998). Drawings and the design process: A review of protocol studies in design and other disciplines and related research in cognitive psychology. *Design Studies*, *19*(4), 389–430.

Rahimian, F. P., Ibrahim, R., Rahmat, R. W. B. O. K., Abdullah, M. T. B., & Jaafar, M. S. B. Hj. (2011). Mediating cognitive transformation with VR 3D sketching during conceptual architectural design process. *ArchNet-IJAR: International Journal of Architectural Research*, *5*(1), 99–113.

Renkl, A. (2005). The worked-out-example principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 229–245). Cambridge University Press.

Renkl, A., & Atkinson, R. K. (2003). Structuring the transition from example study to problem solving in cognitive skill acquisition: A cognitive load perspective. *Educational Psychologist*, *38*(1), 15–22.

Rheingold, H. (1991). *Virtual reality: Exploring the brave new technologies*. Simon & Schuster Adult Publishing Group.

Rhodes, M. (1961). An analysis of creativity. *Phi Delta Kappan*, *42*(7), 305–310.

Rietzschel, E. F., Slijkhuis, J. M., & Van Yperen, N. W. (2014). Task structure, need for structure, and creativity. *European Journal of Social Psychology*, *44*(4), 386–399.

Robertson, G. G., Card, S. K., & Mackinlay, J. D. (1993). Three views of virtual reality: Nonimmersive virtual reality. *Computer*, *26*(2), 81.

Robertson, T. (1997). Cooperative work and lived cognition: A taxonomy of embodied actions. In *Proceedings of the Fifth European Conference on Computer Supported Cooperative Work* (pp. 205–220). Springer.

Robinson, J.W. (2001) The form and structure of architectural knowledge: From practice to discipline. In J. W. Robinson & A. Piotrowski (Eds.), *The discipline of architecture* (pp. 61–82). University of Minnesota Press.

Rosenman, M. A., & Gero, J. S. (1993). Creativity in design using a prototype approach. In J. S. Gero, and M. L. Maher (Eds.), *Modeling creativity and knowledge-based creative design* (pp. 119–145). Lawrence Erlbaum.

Runco, M. A. (2008). Commentary: Divergent thinking is not synonymous with creativity. *Psychology of Aesthetics, Creativity, and the Arts, 2*(2), 93–96.

Salamin, P., Thalmann, D., & Vexo, F. (2006). The benefits of third-person perspective in virtual and augmented reality? In *VRST '06: Proceedings of the ACM symposium on virtual reality software and technology* (pp. 27–30). https://doi.org/10.1145/1180495.1180502

Serino, S., Pedroli, E., Keizer, A., Triberti, S., Dakanalis, A., Pallavicini, F., Chirico, A., & Riva, G. (2016). Virtual reality body swapping: A tool for modifying the allocentric memory of the body. *Cyberpsychology, Behavior, and Social Networking*, *19*(2), 127–133.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*(3972), 701–703.

Sheridan, T. B. (1995). Teleoperation, telerobotics and telepresence: A progress report. *Control Engineering Practice*, *3*(2), 205–214.

Shih, Y. T., Sher, W. D., & Taylor, M. (2015). Understanding creative design processes by integrating sketching and CAD modelling design environments: A preliminary protocol result from architectural designers. *International Journal of Architectural Research: ArchNet-IJAR*, *9*(3), 76–92.

Shih, Y. T., Sher, W. D., & Taylor, M. (2017). Using suitable design media appropriately: Understanding how designers interact with sketching and CAD modelling in design processes. *Design Studies*, *53*, 47–77.

Short, J., Williams, E., & Christie, B. (1976). *The social psychology of telecommunications*. John Wiley & Sons.

Silvia, P. J., Wigert, B., Reiter-Palmon, R., & Kaufman, J. C. (2012). Assessing creativity with self-report scales: A review and empirical evaluation. *Psychology of Aesthetics, Creativity, and the Arts*, *6*(1), 19–34.

Sjölinder, M. (1998). Spatial cognition and environmental descriptions. In N. Dahlbäck (Ed.), *Exploring navigation: Towards a framework for design and evaluation of* *navigation in electronic spaces* (4th ed., pp. 47–58). Swedish Institute of Computer Science.

Slater, M., Spanlang, B., & Corominas, D. (2010). Simulating virtual environments within virtual environments as the basis for a psychophysics of presence. *ACM Transactions on Graphics (TOG)*, *29*(4), 1–9.

Slater, M., Spanlang, B., Sanchez-Vives, M. V., & Blanke, O. (2010). First person experience of body transfer in virtual reality. *PLoS One*, *5*(5), Article e10564.

Slater, M., & Usoh, M. (1993). Representations systems, perceptual position, and presence in immersive virtual environments. *Presence: Teleoperators & Virtual Environments*, *2*(3), 221–233.

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators & Virtual Environments*, *6*(6), 603–616.

Slijepcevic, N. (2013). *The effect of augmented reality treatment on learning, cognitive load, and spatial visualization abilities* [Doctoral dissertation, University of Kentucky]. https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=1003&context=edc_etds

Steed, A., Pan, Y., Zisch, F., & Steptoe, W. (2016, March 19–23). The impact of a self-avatar on cognitive load in immersive virtual reality. In T. Höllerer, V. Interrante, A. Lécuyer, & E. Suma (Eds.), *Proceedings of the 2016 IEEE Virtual Reality Conference* (pp. 67–76). IEEE. https://doi.org/10.1109/VR.2016.7504689

Stones, C., & Cassidy, T. (2007). Comparing synthesis strategies of novice graphic designers using digital and traditional design tools. *Design Studies*, *28*(1), 59–72.

Subrahmanyam, K., & Greenfield, P. M. (1994). Effect of video game practice on spatial skills in girls and boys. *Journal of Applied Developmental Psychology*, *15*(1), 13–32.

Sun, G., & Yao, S. (2012, September). Investigating the relation between cognitive load and creativity in the conceptual design process. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *56*(1), 308–312.

Sutton, K. J., & Williams, A. P. (2007, November 12–15). *Spatial cognition and its implications for design* [Paper presentation]. 2007 Conference of the International Association of Societies of Design Research, Hong Kong, China.

Suwa, M., Purcell, T., & Gero, J. (1998). Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions. *Design Studies*, *19*(4), 455–483.

Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction*, *4*(4), 295–312.

Sweller, J. (2010). Cognitive load theory: Recent theoretical advances. In J. L. Plass, R. Moreno, & R. Brünken (Eds.), Cognitive load theory (pp. 29–47). Cambridge University Press. https://doi.org/10.1017/CBO9780511844744.004

Sweller, J. (2011). Cognitive load theory. In J. P. Mestre & B. H. Ross (Eds.), *Psychology of learning and motivation* (Vol. 55, pp. 37–76). Academic Press.

Sweller, J., Van Merriënboer, J. J., & Paas, F. G. (1998). Cognitive architecture and instructional design. *Educational Psychology Review*, *10*(3), 251–296.

Szulewski, A., Gegenfurtner, A., Howes, D. W., Sivilotti, M. L., & van Merriënboer, J. J. G. (2017). Measuring physician cognitive load: Validity evidence for a physiologic and a psychometric tool. *Advances in Health Sciences Education, 22*(4), 951–968.

Tang, H. H., & Gero, J. S. (2002). A cognitive method to measure potential creativity in designing. In C. Bento, A. Cardoso, & G. Wiggins (Eds.), *Workshop 17–Creative Systems: Approaches to Creativity in Artificial Intelligence and Cognitive Science* (Vol. 17, pp. 47–54). ECAI-02.

Tashakkori, A., & Teddlie, C. (2008). Introduction to mixed method and mixed model studies in the social and behavioral sciences. In V. L. Plano Clark & J. W. Creswell (Eds.), *The mixed methods reader* (pp. 7–26). SAGE Publishing.

Taylor, C. (1995). *Philosophical arguments*. Harvard University Press.

Teddlie, C., & Yu, F. (2007). Mixed methods sampling: A typology with examples. *Journal of Mixed Methods Research*, *1*(1), 77–100.

Thornhill-Miller, B., & Dupont, J. M. (2016). Virtual reality and the enhancement of creativity and innovation: Under recognized potential among converging technologies? *Journal of Cognitive Education and Psychology*, *15*(1), 102–121.

Thurstone, L. L. (1938). *Primary mental abilities* (Vol. 119). University of Chicago Press.

Torrance, E. P. (1988). The nature of creativity as manifest in its testing. In R. J. Sternberg (Ed.), *The nature of creativity* (pp. 43–75). Cambridge University Press.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: When, why, and how? In B. H. Ross (Ed.), *Psychology of learning and motivation* (Vol. 57, pp. 147–181). Academic Press.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, *47*(2), 599–604.

Verbeek, P. P. (2005). *What things do: Philosophical reflections on technology, agency, and design*. Penn State Press.

Vorstenbosch, M. A., Klaassen, T. P., Donders, A. R. T., Kooloos, J. G., Bolhuis, S. M., & Laan, R. F. (2013). Learning anatomy enhances spatial ability. *Anatomical Sciences Education*, *6*(4), 257–262.

Wang, R., Newton, S., & Lowe, R. (2015). Experiential learning styles in the age of a virtual surrogate. *International Journal of Architectural Research: ArchNet-IJAR*, *9*(3), 93–110.

Wiebe, E. N., Roberts, E., & Behrend, T. S. (2010). An examination of two mental workload measurement approaches to understanding multimedia learning. *Computers in Human Behavior*, *26*(3), 474–481.

Wierwille, W. W., & Eggemeier, F. T. (1993). Recommendations for mental workload measurement in a test and evaluation environment. *Human Factors*, *35*(2), 263–281.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*(4), 625–636.

Winograd, T., & Flores, F. F. (1986). *Understanding computers and cognition: A new foundation for design*. Intellect Books.

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence*, *7*(3), 225–240.

Wu, S., Cheng, C. K., Feng, J., D'Angelo, L., Alain, C., & Spence, I. (2012). Playing a first-person shooter video game induces neuroplastic change. *Journal of Cognitive Neuroscience*, *24*(6), 1286–1293.

Xiao, Y. M., Wang, Z. M., Wang, M. Z., & Lan, Y. J. (2005). The appraisal of reliability and validity of subjective workload assessment technique and NASA-task load index. *Zhonghua lao dong wei sheng zhi ye bing za zhi [Chinese Journal of Industrial Hygiene and Occupational Diseases]*, *23*(3), 178–181.

Yang, X., Lin, L., Cheng, P. Y., Yang, X., Ren, Y., & Huang, Y. M. (2018). Examining creativity through a virtual reality support system. *Educational Technology Research and Development*, *66*(5), 1231–1254.

Yu, R., Gero, J. S., Ikeda, Y., Herr, C. M., Holzer, D., Kaijima, S., & Schnabel, A. (2015). An empirical foundation for design patterns in parametric design.

In *Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Daegu, South Korea, May* (pp. 20–23).

Yu, R., Gu, N., & Lee, J. H. (2013). Comparing designers' behavior in responding to unexpected discoveries in parametric design environments and geometry modeling environments. *International Journal of Architectural Computing*, *11*(4), 393–414.

Yüksel, N. S. (2017). Measuring spatial visualization: Test development study. In M. S. Khine (Ed.), *Visual-spatial Ability in STEM Education* (pp. 59–84). Springer.

Zacks, J. M., Mires, J., Tversky, B., & Hazeltine, E. (2000). Mental spatial transformations of objects and perspective. *Spatial Cognition and Computation*, *2*(4), 315–332.

Appendix A

Pre-Intervention Questionnaire

Demographics

1. What is your age?

   Mark only one oval.

   - 18-24
   - 25-30
   - 31-40
   - Other

2. What is your gender?

   Mark only one oval.

   - Male
   - Female
   - Other
   - Prefer not to say

3. What is your Ethnicity?

Mark only one oval.

- White/Causcasian
- Black/African American
- Hispanic/Latino
- Asian/Pacific Islander
- Native American
- Other
- Prefer not to say

4. Academic year?

Mark only one oval.

- Freshmen
- Sophomore
- Junior
- Senior
- Graduate

Please select the most appropiate response to the following as they relate to you.

5. Do things that others find strange

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

6. Like to get lost in thought

Mark only one oval.

- ⬭ Very Inaccurate
- ⬭ Moderately Inaccurate
- ⬭ Neither Inaccurate nor Accurate
- ⬭ Moderately Accurate
- ⬭ Very Accurate

7. Enjoy wild flights of fantasy

Mark only one oval.

- ⬭ Very Inaccurate
- ⬭ Moderately Inaccurate
- ⬭ Neither Inaccurate nor Accurate
- ⬭ Moderately Accurate
- ⬭ Very Accurate

8. Do things by the book

Mark only one oval.

- ⬭ Very Inaccurate
- ⬭ Moderately Inaccurate
- ⬭ Neither Inaccurate nor Accurate
- ⬭ Moderately Accurate
- ⬭ Very Accurate

9. Love to daydream

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

10. Swim againts the current

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

11. Like to solve complex problems

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

12. Am not interested in abstract ideas

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

13. Love to read challenging material

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

14. Seldom get lost in thought

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

15. Have a vivid imagination

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

16. Know how things work

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

17. Am not interested in theoretical discussion

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

18. Seldom daydream

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

19. Take deviant positions

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

20. Try to avoid complex people

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

21. Avoid difficult reading material

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

22. Do unexpected things

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

23. Do not have a good imagination

Mark only one oval.

- Very Inaccurate
- Moderately Inaccurate
- Neither Inaccurate nor Accurate
- Moderately Accurate
- Very Accurate

24. Love to think up new ways of doing things

Mark only one oval.

- ⬭ Very Inaccurate
- ⬭ Moderately Inaccurate
- ⬭ Neither Inaccurate nor Accurate
- ⬭ Moderately Accurate
- ⬭ Very Accurate

Post-Intervention Questionnaire

* Required

The following questions are in a 1 to 5 scale, where 1 is the lowest and 5 the highest.

1. How strong was your sense of "being there" in the virtual environment?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

2. How strong was your sense of inclusion in the virtual environment?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

3. How aware were you of the real world surroundings while moving through the virtual world (i.e., sounds, room temperature, other people, etc.)?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

4. How compelling was your sense of being present in a virtual world?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

5. How involved were you in the virtual environment experience?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

6. In general, how realistic did the virtual world appear to you?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

7. Do you feel that you could have reached into the virtual world and grasped an object?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

8. How much did the visual aspects of the environment involve you?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

9. How well could you examine objects from multiple viewpoints?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

10. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

11. How responsive was the environment to actions that you initiated (or performed)?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

12. How much delay did you experience between your actions and expected outcomes?

Mark only one oval.

	1	2	3	4	5	
Low	⬭	⬭	⬭	⬭	⬭	High

13. How natural did your interactions with the environment seem?

Mark only one oval.

	1	2	3	4	5	
Low	⬭	⬭	⬭	⬭	⬭	High

14. How much were you able to control events?

Mark only one oval.

	1	2	3	4	5	
Low	⬭	⬭	⬭	⬭	⬭	High

15. How realistic were the virtual world's reactions to your actions?

Mark only one oval.

	1	2	3	4	5	
Low	⬭	⬭	⬭	⬭	⬭	High

16. How much did your experiences in the virtual environment seem consistent with your real-world experiences?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

17. How well could you move or manipulate objects in the virtual environment?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

18. How much did the control devices interfere with the performance of assigned tasks or with other activities?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

19. How much did you feel your body was part of the virtual world?

Mark only one oval.

	1	2	3	4	5	
Low	◯	◯	◯	◯	◯	High

20. How natural was the mechanism which controlled movement through the environment?

Mark only one oval.

	1	2	3	4	5	
Low	⬭	⬭	⬭	⬭	⬭	High

The following Questions are in a 1 to 5 scale where 1 is "strongly disagree" and 5 is "strongly agree".

21. You did not feel present in the virtual space.

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

22. In the computer generated world you had a sense of "being there".

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

23. You felt you were physically present in the virtual world.

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	Strongly Agree

24. You felt you behaved in the virtual world as you do in real life.

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

25. The movements in the virtual world seemed natural to you.

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

26. You could interact and manipulate objects in the virtual world as if you were in the real world.

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	◯	◯	◯	◯	◯	Strongly Agree

Overall

27. If your level in the real world is 100, and your level of presence is 1 if you have no presence, rate your level of presence in this virtual world (presence is a "feeling of being there").

Enter a number 1-100.

____

Untitled Section

Please select how much each sympton below is affecting you right now.

28. General Discomfort

Mark only one oval.

- None
- Slight
- Moderate
- Severe

29. Fatigue

Mark only one oval.

- None
- Slight
- Moderate
- Severe

30. Headache

Mark only one oval.

- None
- Slight
- Moderate
- Severe

31. Eye Strain

Mark only one oval.

- ( ) None
- ( ) Slight
- ( ) Moderate
- ( ) Severe

32. Difficulty Focusing

Mark only one oval.

- ( ) None
- ( ) Slight
- ( ) Moderate
- ( ) Severe

33. Salivation Increasing

Mark only one oval.

- ( ) None
- ( ) Slight
- ( ) Moderate
- ( ) Severe

34. Sweating

Mark only one oval.

- None
- Slight
- Moderate
- Severe

35. Nausea

Mark only one oval.

- None
- Slight
- Moderate
- Severe

36. Difficulty Concentrating

Mark only one oval.

- None
- Slight
- Moderate
- Severe

37. "Fullness of Head"

Mark only one oval.

- None
- Slight
- Moderate
- Severe

38. Blurred Vision

Mark only one oval.

- None
- Slight
- Moderate
- Severe

39. Dizziness with Eyes Opened

Mark only one oval.

- None
- Slight
- Moderate
- Severe

40. Dizziness with Eyes Closed

Mark only one oval.

- None
- Slight
- Moderate
- Severe

41. Vertigo

Vertigo is experienced as loss of orientation with respect to vertical upright.

Mark only one oval.

- None
- Slight
- Moderate
- Severe

42. Stomach Awareness

Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Mark only one oval.

- None
- Slight
- Moderate
- Severe

43. Burping

Mark only one oval.

- None
- Slight
- Moderate
- Severe

Untitled Section

44. In the activity I just finished, I invested: *

Mark only one oval.

- very, very low mental effort
- very low mental effort
- low mental effort
- rather low mental effort
- neither low nor high mental effort
- rather high mental effort
- high mental effort
- very high mental effort
- very, very high mental effort

45. How mentally demanding was the task? *

Mark only one oval.

	1	2	3	4	5	
Very low						Very high

46. How physically demanding was the task? *

Mark only one oval.

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

47. How hurried or rushed was the pace of the task? *

Mark only one oval.

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

48. How successful were you in accomplishing what you were asked to do? *

Mark only one oval.

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

49. How hard did you have to work to accomplish your level of performance? *

Mark only one oval.

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

50. How insecure, discouraged, irritated, stressed, and annoyed were you? *

Mark only one oval.

	1	2	3	4	5	
Very low	◯	◯	◯	◯	◯	Very high

Thank you for your time and collaboration

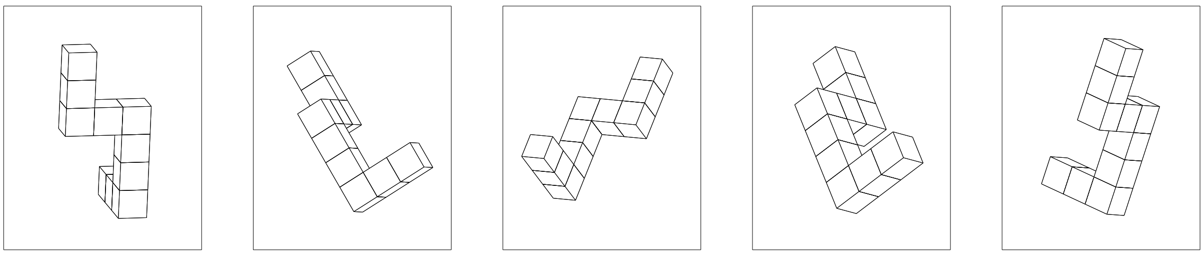
Further questions feel free to contact Luis Mejia at lmejiap@okstate.edu

Appendix C

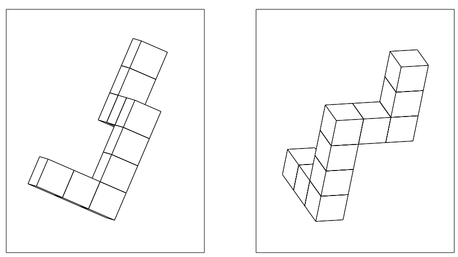
MENTAL ROTATIONS TEST (MRT-A)

This test is composed of the figures provided by Shepard and Metzler (1978), and is, essentially, an Autocad-redrawn version of the Vandenberg & Kuse MRT test.

Please look at these five figures



Note that these are all pictures of the same object which is shown from different angles. Try to imagine moving the object (or yourself with respect to the object), as you look from one drawing to the next.

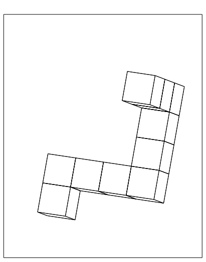


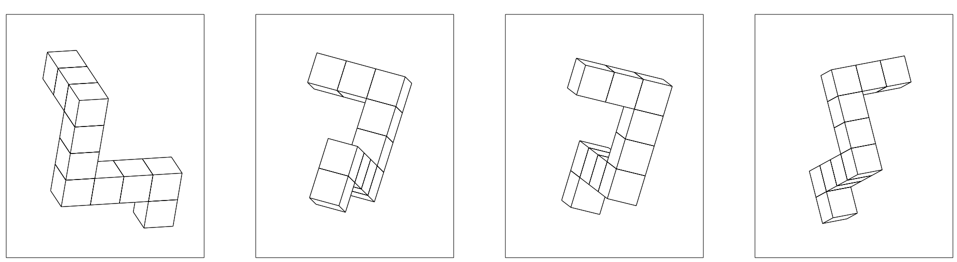
Here are two drawings of a new figure that is different from the one shown in the first 5 drawings. Satisfy yourself that these two drawings show an object that is different and cannot be "rotated" to be identical with the object shown in the first five drawings.

Now look at this object:

Two of these four drawings show the same object. Can you find those two? Put a big X across them.

1.

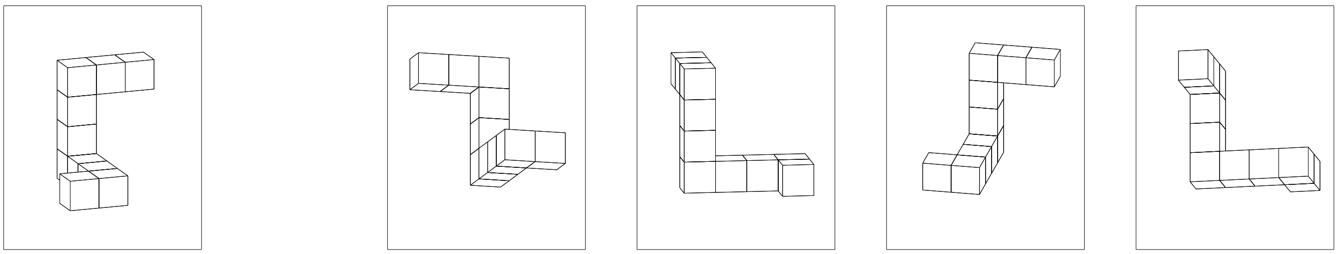




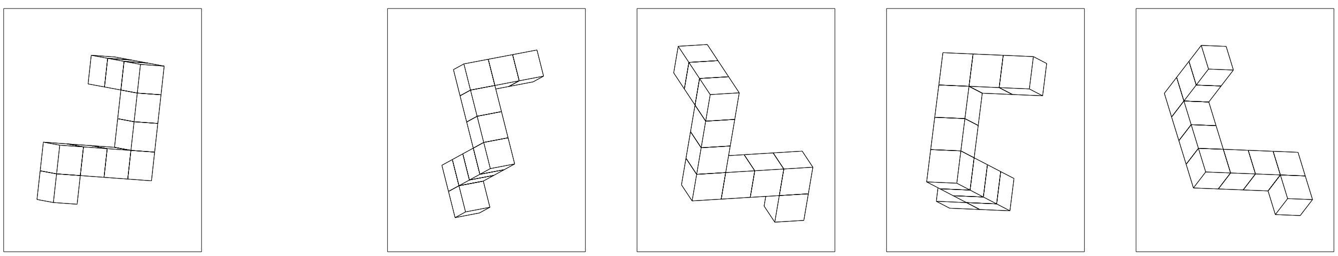
If you marked the first and third drawings, you made the correct choice.

Here are three more problems. Again, the target object is shown twice in each set of four alternatives from which you choose the correct ones.

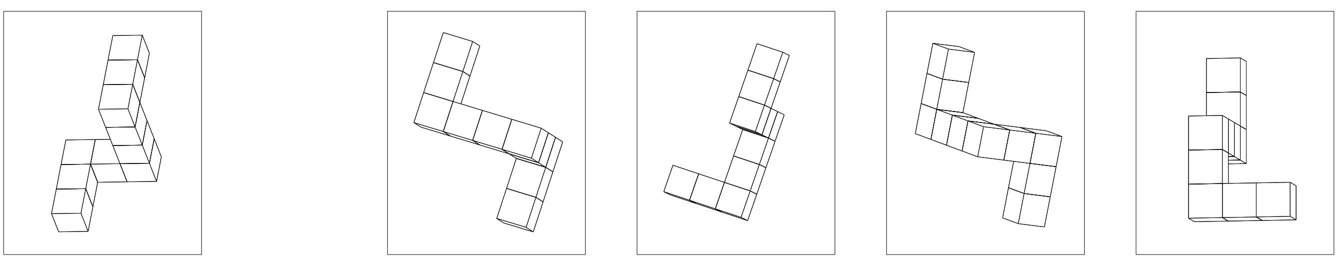
2.a



3.a



4.a

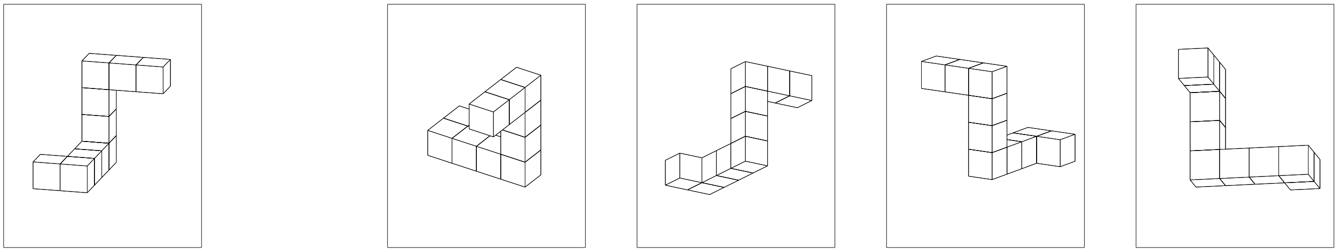


Correct Choice: 2: second and third
3: first and fourth
4: first and third

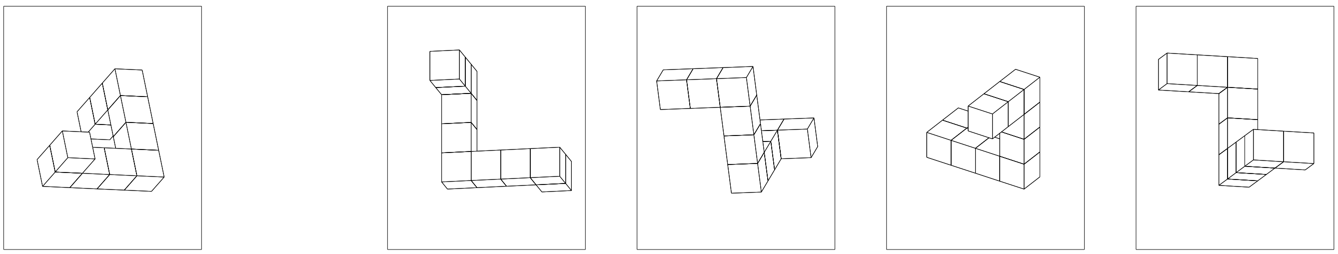
When you do the test, please remember that for each problem set there are two and only two figures that match the target figure.

You will only be given a point if you mark off both correct matching figures, marking off only one of these will result in no marks.

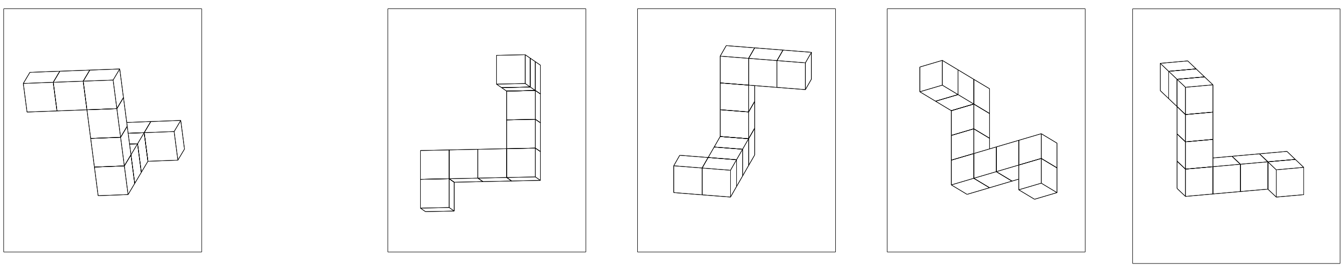
1.a



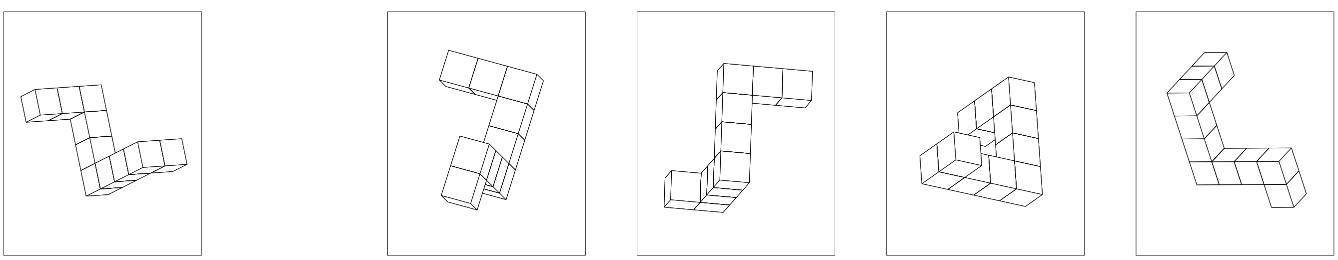
2.a



3.a



4.a



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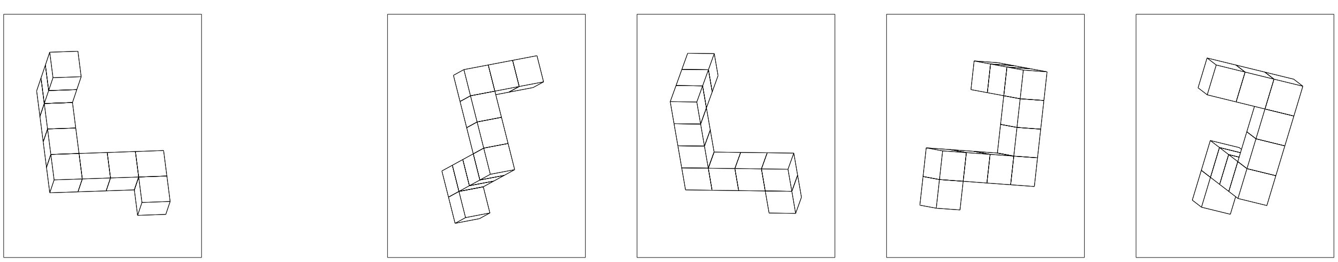

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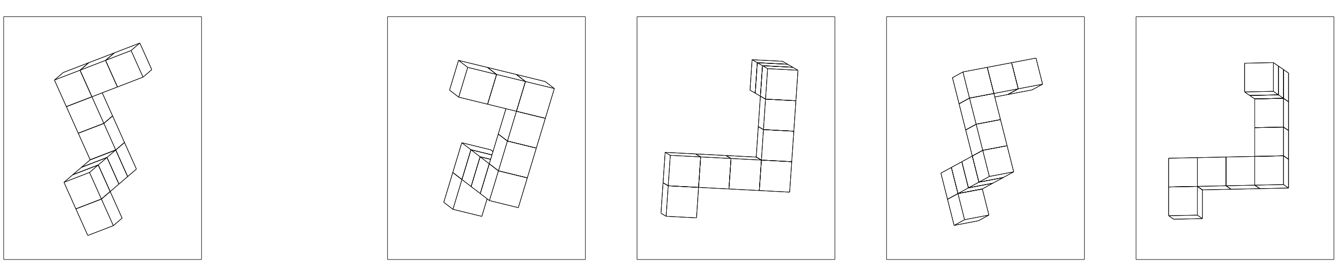

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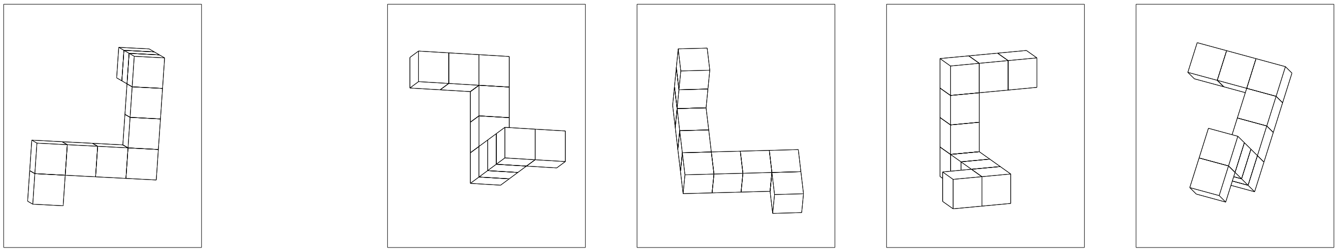

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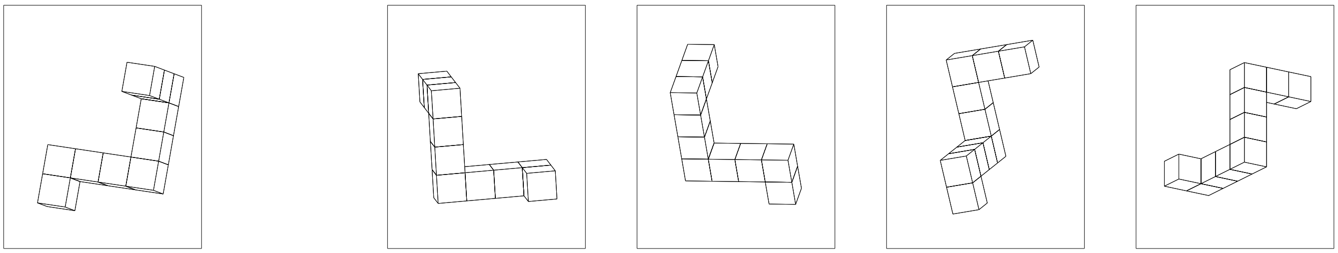

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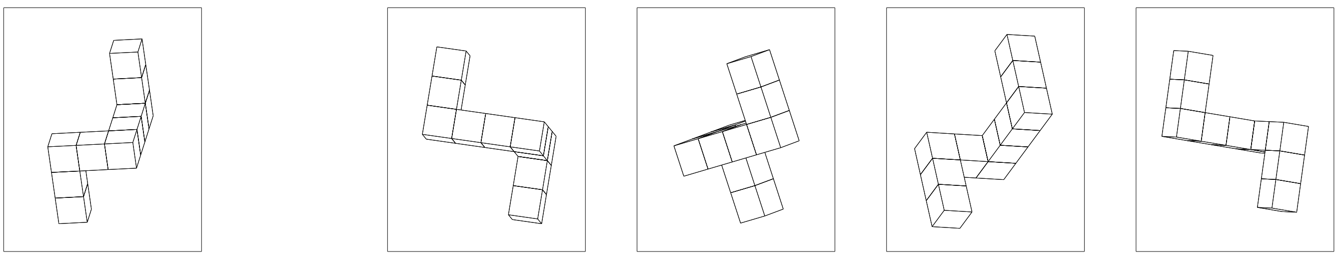

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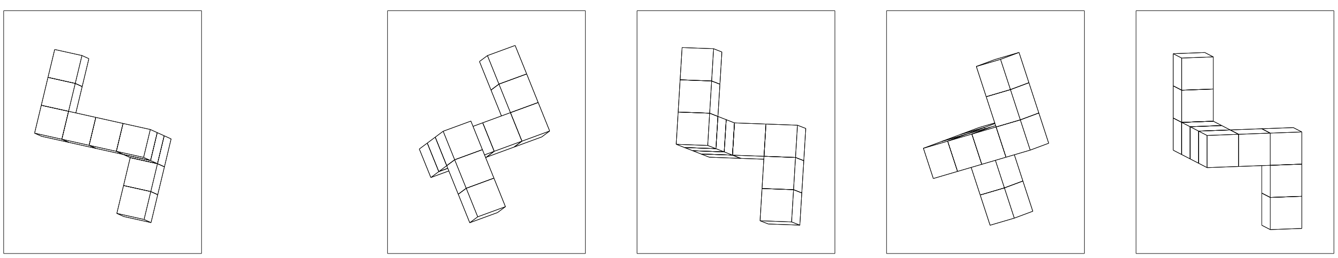

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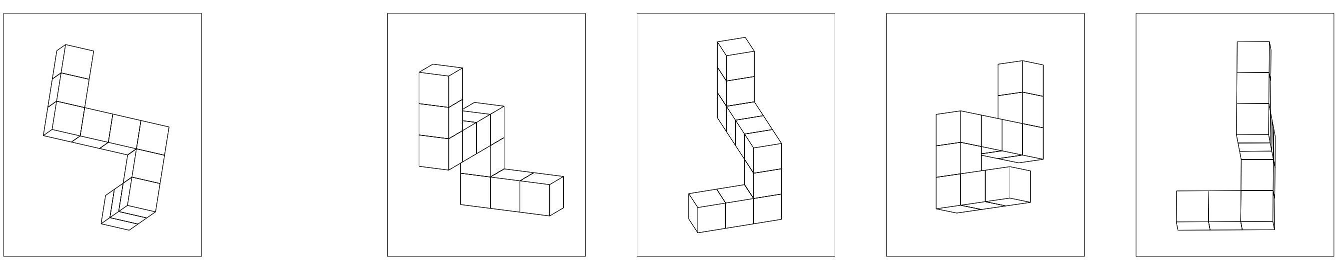

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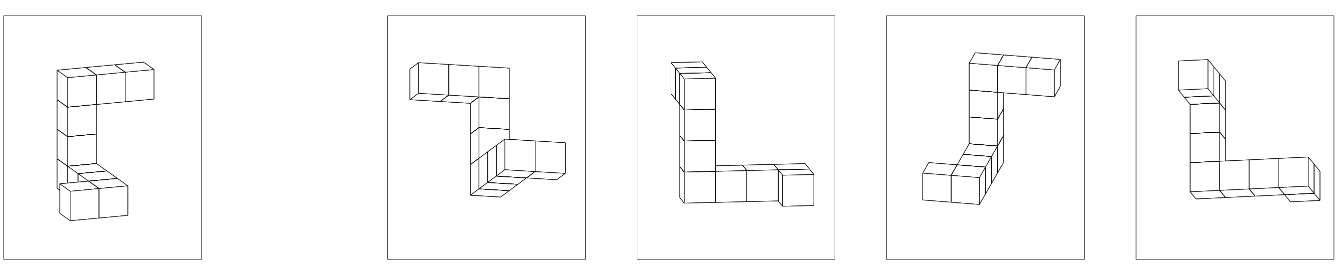

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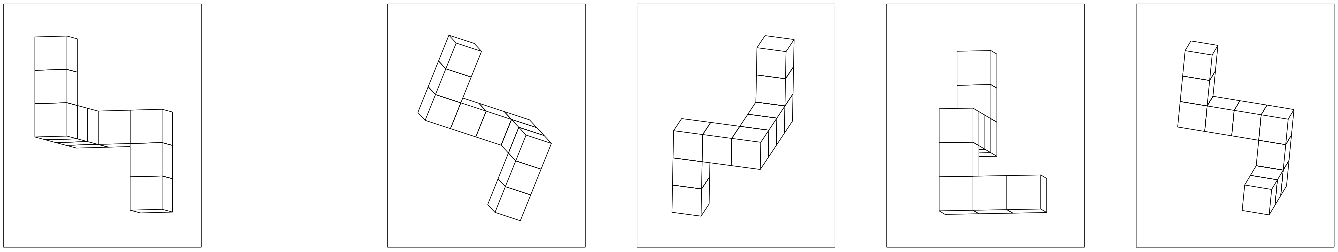

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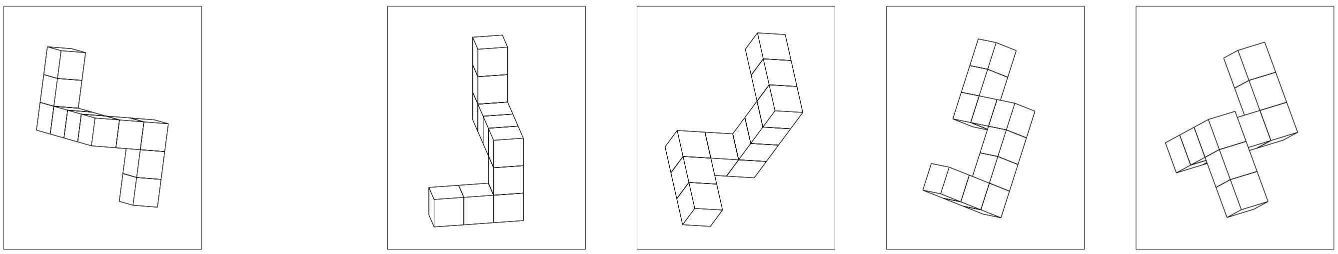

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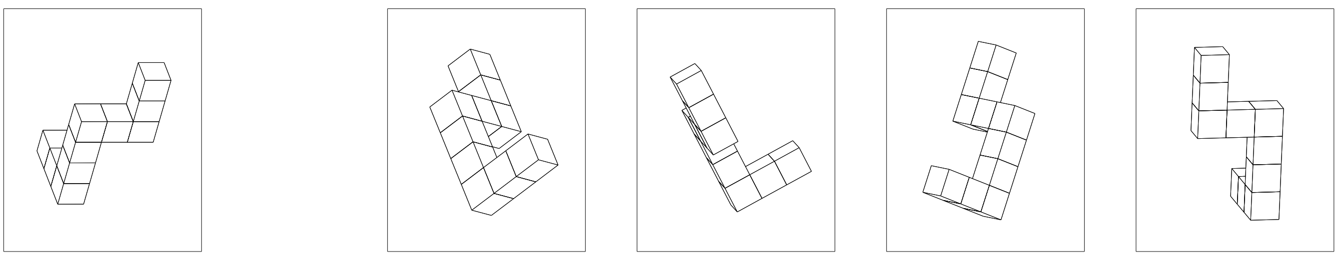

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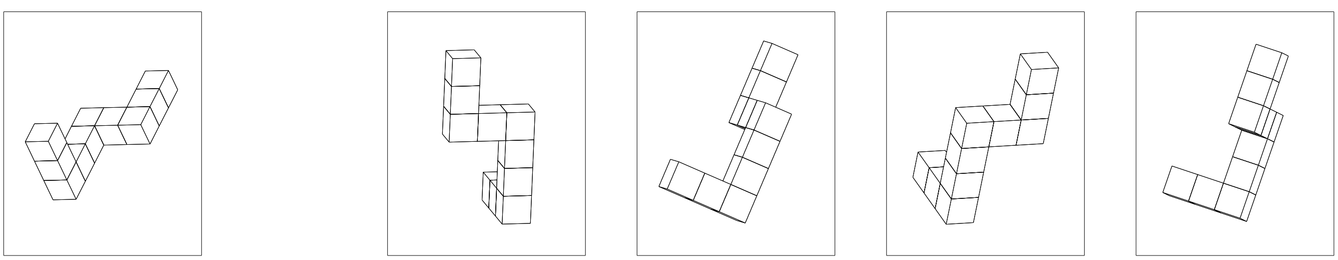

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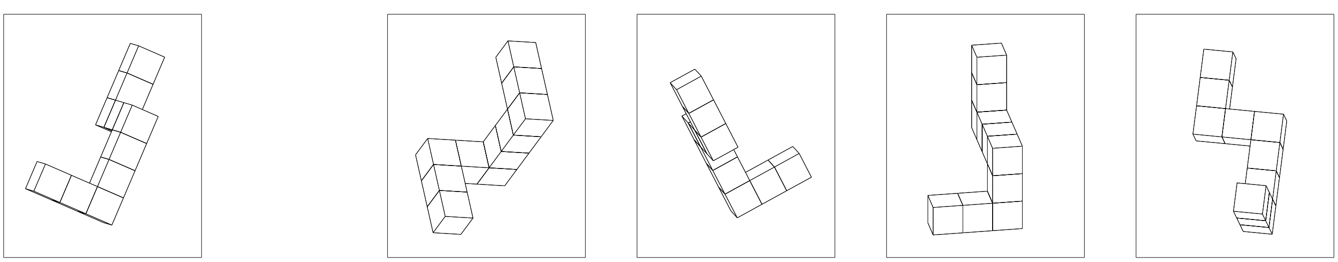

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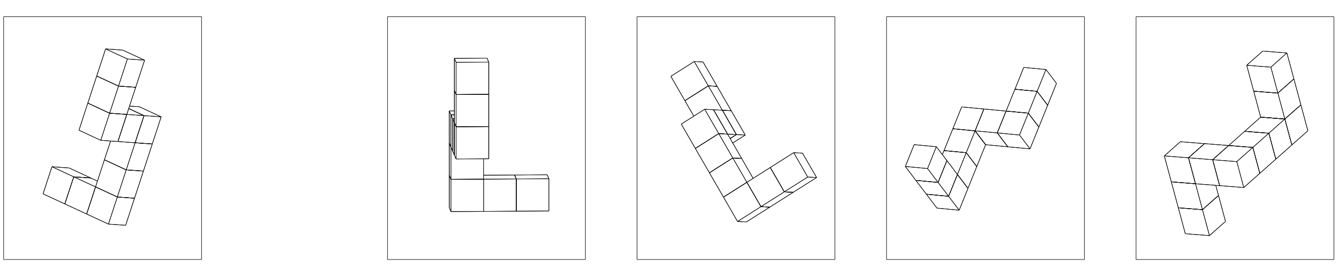

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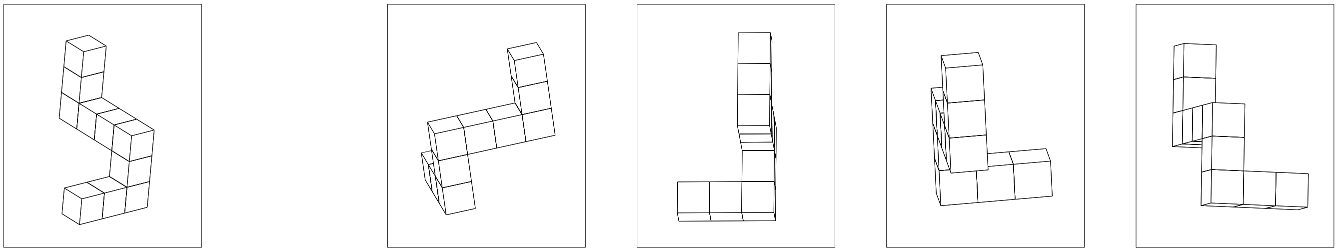

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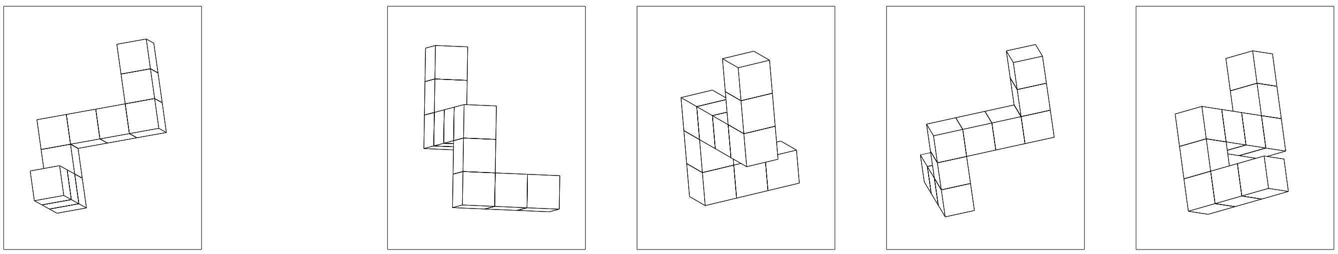

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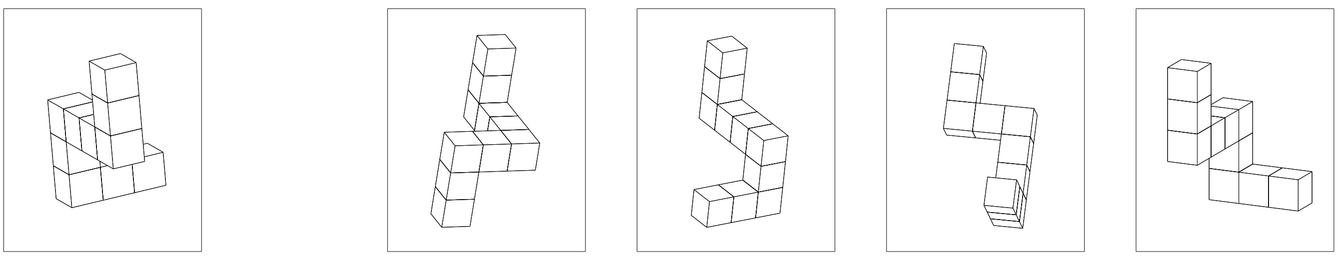

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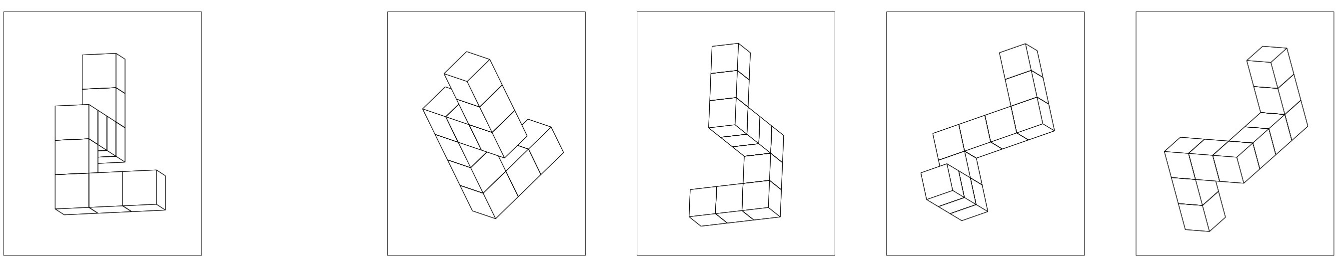

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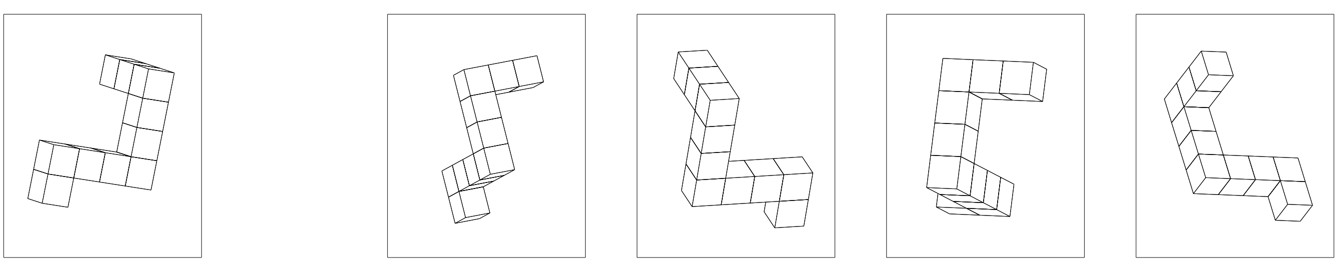

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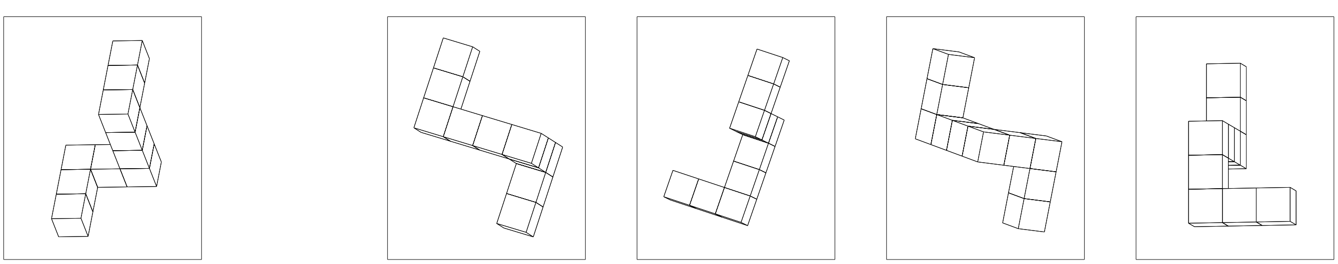

Appendix D

A Mars Challenge in 2035

It is the year 2035 and finally human kind has installed the first space station in mars. As a designer you have been invited to participate in exploring multiple possibilities of the new modular storage system developed in collaboration between NASA and SpaceX.

The system is comprised of modules available in nine different volumes. *Figure 1. displays the nine size options.*

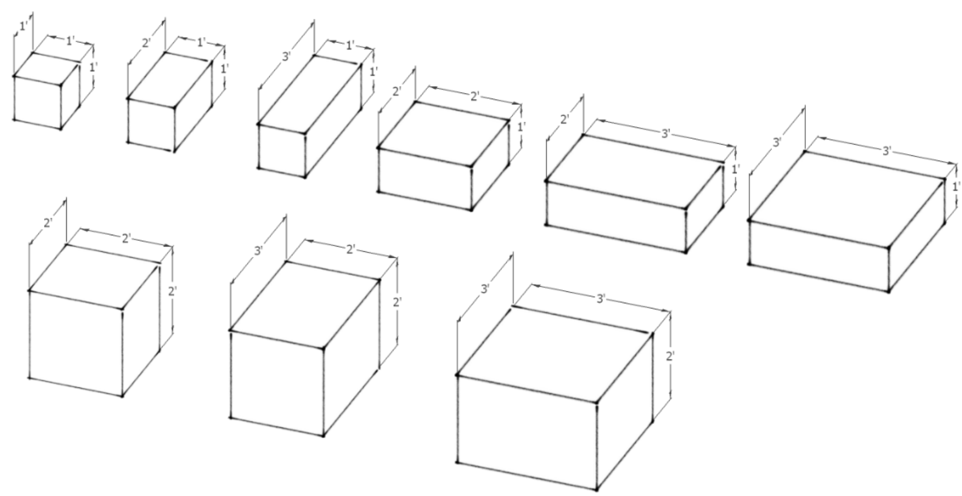

Figure 1. Module Options

These modules can be manufactured in three different materials. The first material is a thermal material which can manipulate temperature of the content or the exterior surface. The second material is a very robust and lightweight material based on Kevlar and Carbon Fiber blending that has ballistic resistance with extreme lightweight. The final material is a new composite based in Aramid and new polymeric structures which permits structural rigidity but surface flexibility. One of the main attributes of this new modular system is that the modules are able to interlock between one another by generating contact between the faces.

RED = Thermal
BLUE = Ballistic resistance
GREEN = Flexibility

The modules are to be filled with three basic contents. The first content is constituted of bio-digestible elements, more specifically food and water reserves intended for daily consumption. The second content is flammable oxygen pipets used for space walks and outdoor activities. The third content is medical supplies intended for emergency situations or daily wellbeing.

Your mission, if you choose to accept it, is to explore a modular configuration for storage of the three contents (food/water, oxygen and medicine).

Food

Oxygen

Medicine

You may choose as many modules as you want from the available sizes in any of the three proposed materials. In each container, you will store one of the available contents. Previously, these modules were stacked as a pile of bricks and this occasioned astronauts' boredom and elicited some depressing tendencies in them. Hence, as a designer, you are encouraged to generate a sculpture-like distribution of the modules that may have some alternative use beside storage. You are constrained in the overall size of you sculpture by a cubic volume of 5 x 5 x 5 feet.

Your design, will be placed in a space module of 8 x 12 feet and 8 feet tall, that has two entrances in the minor walls, one of which connects to the outside of the space station and the other to a social and dining area. One of the main walls of this space is attached to the energy module of the space station, and the opposite wall has a panoramic window with a superb view of the earth and the stellar surroundings. *Figure 2. displays the overall plan of the destined space.*

A quick step by step guide.

1. Select the module size you want to fill
2. Select the content you want to pack.
3. Select the material you want that module to have
4. Arrange the module in the space considering the environment and other modules.

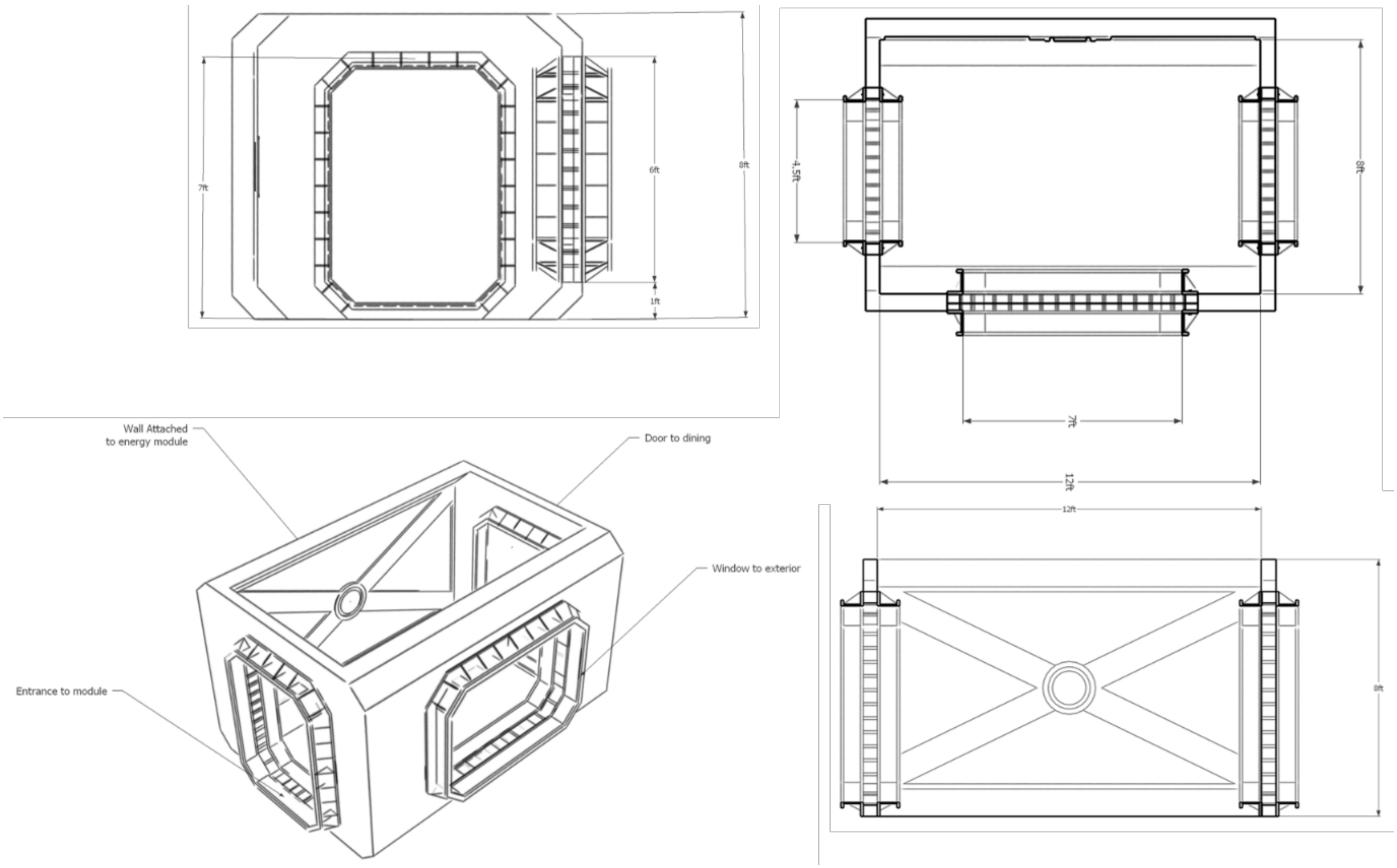

Figure 2. General plans

Appendix E

Creative Product Semantic Scale (CPSS) + Creativity Assessment.

For each of the design outcomes use the five scales for novelty, resolution and elaboration & synthesis to rate the composition. For instance, provide a rating of 1- if you think the proposal is overused and 7- if it is fresh from a novelty standpoint. 4- is the mid-point, so, if you think the proposal is neither overused or fresh, you would give it a 4.

	1	2	3	4	5	6	7
Novelty							
Overused-Fresh							
Predictable-Novel							
Usual-Unusual							
Unique-Ordinary							
Original-Conventional							
Resolution							
Illogical-Logical							
Makes sense-senseless							
Irrelevant-Relevant							
Appropriate-Inappropriate							
Adequate-Inadequate							
Elaboration & Synthesis							
Integrated - Scattered							
Polished - Unpolished							
Refined - Unrefined							
Inadequate - Adequate							
Deliberate - Undeliberate							
Geometric - Organic							
Undetailed - Detailed							
Balanced - Unbalanced							
Incoherent - Coherent							
Harmonious - Discordant							

From:	IRB Office
To:	Mejia Puig, Luis; Mejia Puig, Luis; Chandrasekera, Tilanka
Subject:	Approval of Expedited IRB Application IRB-20-134
Date:	Wednesday, March 25, 2020 12:49:20 PM

Dear Luis Mejia Puig,

The Oklahoma State University Institutional Review Board (IRB) has approved the following application:

Application Number: IRB-20-134
PI: Luis Mejia Puig
Title: Psyco-physiological measurements in Immersive Virtual Reality (VR)
Review Level: Expedited

You will find a copy of your Approval Letter in IRBManager. Click IRB - Initial Submission to go directly to the event page. Please click attachments in the upper left of the screen. The approval letter is under "Generated Docs." Stamped recruitment and consent documents can also be found in this location under "Attachments". Only the approved versions of these documents may be used during the conduct of your research.

<u>As Principal Investigator, it is your responsibility to do the following:</u>

- Conduct this study exactly as it has been approved. Any modifications to the research protocol must be submitted for IRB approval before implementation.
- Submit a request for continuation if the study extends beyond the approval period.
- Report any adverse events to the IRB Chair within 5 days. Adverse events are those which are unanticipated and impact the subjects during the course of the research; and
- Notify the IRB office when your research project is complete by submitting a closure form via IRBManager.

Please note that approved protocols are subject to monitoring by the IRB and that the IRB office has the authority to inspect research records associated with this protocol at any time. If you have questions about the IRB procedures or need any assistance from the Board, please contact the IRB office at 405-744-3377 or irb@okstate.edu.

Best of luck with your research,

Sincerely,

Dawnett Watkins, CIP
Whitney McAllister, MS

Oklahoma State University
Institutional Review Board
Office of University Research Compliance
223 Scott Hall, Stillwater, OK 74078
Website: https://irb.okstate.edu/

Ph: 405-744-3377 | Fax: 405-744-4335| irb@okstate.edu

VITA

Luis A. Mejia-Puig

Candidate for the Degree of

Doctor of Philosophy

Dissertation: THE VIRTUAL BODY IN IMMERSIVE VIRTUAL REALITY AND ITS INFLUENCE ON CREATIVITY

Major Field: Interior Design

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Interior Design at Oklahoma State University, Stillwater, Oklahoma in July 2021.

Completed the requirements for the Master of Science in Industrial Design and Product development at Universidad Politecnica de Catalunya, Spain in 2003.

Completed the requirements for the Bachelor of Science in Industrial Design at Universidad Pontificia Bolivariana, Colombia in 1999.