Embodied Virtual Reality's Influence on Conceptual Design for Stormwater Infrastructure

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1 ABSTRACT

The conceptual design process provides the first visual cue to link the designer to the end user but does not always align the goals, needs, and desires of various stakeholders. In essence, conceptual designs may inhibit design processes if the designer misinterprets the perspectives of important stakeholders, including wildlife. As a result, the type and quality of ideas that are explored in the conceptual design phase can be altered, which may set the tone for later design phases. Embodiment is a concept through virtual reality (VR) in which an individual can artificially become a different stakeholder and take another perspective. This research employs an embodied virtual reality experiment to discover if this form of VR affects ideation during the conceptual engineering design process. A stormwater-focused case study was utilized, and results demonstrate that embodying another being outside of oneself (e.g., a bird) significantly changes the type of ideas generated as well as the perceived connection to nature. Participants who embodied a bird reported higher nature-relatedness scores and more instances of socioeconomic co-benefits of using green infrastructure, such as increasing park space and walking trails. These results encourage the use of embodied virtual reality within the conceptual engineering design process by influencing the type of ideas generated to align stakeholder needs through different perspectives.

2 INTRODUCTION

Conceptual design is an iterative process that can be enhanced through designers placing themselves "in the shoes" of the end user (Köppen & Meinel, 2015). This form of perspective-taking is often challenging to achieve, in part, because there is no universal approach or agreed-upon method (Singer & Klimecki, 2014). As perspective-taking becomes more effective (meaning the designer can align his or her feelings with end users), the designer is more likely to act and create altruistically (Oswald, 1996), providing tangential benefits to the end user. However, affective perspective-taking requires a "connection" between individuals or groups (Köppen & Meinel, 2015), which various design plan sets, wish lists, pros and cons sheets, and other sources of an initial design fail to induce.

Traditional methods for perspective-taking often occur using inaccessible media, and the communication process between designers and end users is often not easily digestible to a non-technical audience (Cascetta et al., 2015). Current perspective-taking strategies could be improved by more immersive experiences that help connect different groups of people and communicate often complex and technical information in a different format. Immersive experiences are imaginary scenarios that depict real-life, such as the construction of a building without physically having to be on-site (Okeil, 2010).

The benefit of immersive experiences over traditional approaches for perspective taking, like door-to-door canvassing, visual preference surveys, professional design charrettes, and community forums, is the ability to place both the end user and designer into the design itself (Xiang et al., 2021; Xie et al., 2017). Technological improvements such as augmented and virtual reality could have the capability of not only creating more immersive experiences but also providing different lenses of reality to increase perspective-taking and critique.

Virtual reality (VR) enables both designers and stakeholders to interact with the design at scale and has been increasingly utilized in the detailed design process within the last five years. Especially for the design of the built environment, VR provides an accessible vehicle for architects, engineers, contractors, and the public to visually see design ideas about large physical systems and buildings before they are built, as well as to recommend improvements (Coroado, 2015; Ma et al., 2020; Makarova et al., 2015). These studies primarily take place during a detailed design phase, where the ability to ideate is typically less than during a conceptual design phase.

Embodied experiences could benefit the conceptual design process by allowing the designer and the owner to literally consider a different perspective. Embodiment is a form of immersive VR that allows a VR user to interact vicariously through another person or being (Kilteni et al., 2012). The embodiment of a human or nonhuman avatar can produce feelings of empathy by considering various social perspectives (Bertrand et al., 2018; Gerry, 2017; Kors et al., 2020). Avatars provide participants with the ability to "see" through a different set of eyes.

Embodied VR works to change behavior through two lenses: self and other. The self-lens displays the virtual reality participant as a version of him or herself. For example, a negative stereotyping of an elderly individual can be reduced by embodying young individuals as older avatars of themselves (Yee & Bailenson, 2006). The other lens allows the participant to look through the eyes of another person or being. It creates an opportunity to aid the design process and enables the view of a space from a different perspective. Previous studies have discovered that embodiment can altruistically curb an individual's behavior in favor of pro-environmental issues (Schultz, 2000; Yee & Bailenson, 2006). However, these studies do not extend to the conceptual design process, which this research seeks to explore.

The purpose of the research presented in this paper was to explore the influence of embodiment on the conceptual design process. VR acts as a communication platform and embodiment nudges the participant to think, see, and hear in the mindset of another being. By exploring embodiment through VR, the intent of the study was to understand how a specialized form of perspective-taking can influence the conceptual design process and lead to more equitable, inclusion of green infrastructure.

3 LITERATURE REVIEW – VIRTUAL REALITY AND NATURE IN CONCEPTUAL DESIGN

Natural systems are often overlooked and undervalued in the design and development of the built environment. Past theories emphasize the imperative to build with nature for human prosperity (Besthorn & Saleebey, 2003; Grinde & Patil, 2009), which is reflected by several co-benefits not limited to high returns on investment, improved air and water quality, and better health outcomes (Bertram & Rehdanz, 2015). However, those involved in the design process of infrastructure systems, buildings, and urban development commonly design without leveraging the use of nature (Randolph, 2003; Rosenbloom, 2018). The general public also tends to overlook the value of nature in the built environment (Wamsler et al., 2020). In turn, this has opened the need for better communication platforms to facilitate conceptual design, such as VR, to enable new ways of expressing the benefits of nature in design (Scurati et al., 2021).

3.1 Building with nature

The Biophilic Hypothesis posits the requirement for humans to coexist with nature as part of a genetic code (Kellert, 1995, 2018). Biophilic design creates a connection to nature often through using elements of nature in the design of physical spaces. One example of biophilic design is green infrastructure, which uses natural systems to convey and infiltrate stormwater and creates greenness in public areas (Markevych et al., 2017).

Gray infrastructure projects refer to solutions that primarily rely on concrete and steel to move or hold stormwater, whereas green infrastructure projects refer to solutions that rely on elements of nature to move, infiltrate, or hold stormwater (Casal-Campos et al., 2015). Traditionally, grey projects have been those that may include the use of pipes, walls, levees, tunnels, curbs, and gutters to hold or convey stormwater without allowing much infiltration. These measures have been used for much of the 20th century, and the vast majority of U.S. infrastructure comprises these elements (Science, 2015). This type of infrastructure conveys stormwater as quickly as possible away from a site to a receiving water body or holding basin (Galderisi, 2012). Gray infrastructure is especially effective at quickly conveying stormwater because of its low permeability, which reduces the ability for water to infiltrate into the ground.

Examples of green infrastructure projects are rain gardens, bioswales, porous pavements, green roofs, and stream daylighting to convey and infiltrate stormwater. These solutions have been tested to build urban resilience; green infrastructure posits a natural ability for communities to prepare for, absorb, recover from, and adapt to climate and weather-based threats (Van Oijstaeijen et al., 2020). As such, green infrastructure is commonly used in the new urbanist planning approach, which makes land use more intensive and is designed to minimize sprawl (Randolph, 2003).

Green infrastructure has also become a requirement for federally funded projects in the U.S., such as from consent decrees. However, the U.S. government's requirements placed on green infrastructure to capture stormwater are relatively low. For example, Project Clean Lake in Cleveland, Ohio's consent decree only required one percent of incoming stormwater to be absorbed through green infrastructure (EPA, 2011). This relatively limited buy-in to green design enabled a multi-billion dollar effort to construct a 20-mile system of connected tunnels under the city to meet the requirements of the consent decree (NEORSD, 2017).

3.2 Using virtual reality to increase the perceived value of nature

A stronger human-nature connection can lead to more pro-environmental behaviors, such as choosing eco-friendly alternatives for a household, attempting to conserve water and energy, and recycling and composting (Whitburn et al., 2020). By simulating natural environments and allowing individuals to engage in environmentally conscious actions within virtual spaces, VR experiences can deepen people's sense of nature-relatedness and reinforce their commitment to sustainable practices. As Ahn & Bailenson (2012) discuss, pro-environmental behaviors can be enhanced through VR experiences. Ahn and & Bailenson found that asking participants to cut down a virtual tree led to subsequently greater pro-environmental self-efficacy and actual pro-environmental behavior because of the embodied VR experience. This embodied VR experience likely enabled individuals to better understand the consequences of their actions and feel a greater sense of responsibility towards nature. As engineers and the general public alike can overlook the value of natural systems in their cityscapes (Randolph, 2003; Rosenbloom, 2018; Wamsler et al., 2020), strengthening pro-environmental behaviors through embodied VR may help change the perceived value of nature in design.

The use of VR technology seems to promote nature-relatedness and pro-environmental behaviors through the immersive and realistic experience it provides, which may help to evoke an emotional response crucial for developing an empathetic connection with nature. By transporting individuals to virtual natural environments, VR helps to enable them to witness firsthand the beauty, diversity, and vulnerability of ecosystems, or lack of these environments in a place. This enhanced awareness facilitated by VR experiences may help to inspire individuals to take action through their design decisions in both virtual and real-world settings.

VR has been used in prior studies about the design of the built environment, for example, as a tool to boost the interactions of stakeholders (Bartlett et al., 2005; Stauskis, 2014) and preference construction for smart cities (Jamei et al., 2017). Similarly, VR has been used to create altruistic behavior toward the environment, embodying an animal harmed by the increase of pollution and its effect on biospheric health, increasing the likelihood to promote action to reduce emissions (Schultz, 2000). Furthermore, Soliman et al. (2017) and Spangenberger et al. (2022) identified that embodied VR can positively impact one's internal valuation of nature. However, when combined with previous findings from Ahn and Bailenson (2012) on how nature-relatedness impacts pro-environmental behaviors, uncertainty exists about whether a change in nature-relatedness through embodied VR impacts design choices. This gap in knowledge presents an opportunity for further exploration and investigation to better understand the potential of embodied VR experiences in shaping environmentally conscious engineering design and decision-making practices.

4 RESEARCH QUESTION AND HYPOTHESIS

The research question this study aimed to answer was how embodied VR influences engineering conceptual design. The hypothesis was VR enhances designers' perceived connection with nature and this would influence their design. Immersive VR creates a platform that allows designers to see and hear environments in a new way compared to traditional two-dimensional drawings and this may potentially alter how designers and other stakeholder groups weigh design criteria (Coroado, 2015; Wang et al., 2018).

5 METHODS

5.1 Overview

A VR experiment was created to mimic a design charrette. After a case study about combined sewer overflow in Cincinnati, OH was reviewed by participants, they were split into one of three groups: a control group (receiving no VR intervention), a human avatar group (walking through a virtual environment depicting the area of interest), and a bird avatar group (flying through the same area of interest as a bird). Participants then orally described their design changes to the area of interest. Pre and post-experiment Nature Connectedness scales were utilized (Mayer & Frantz, 2004). Natural language processing (NLP) and thematic content analysis (TCA) were used to identify differences in how participants within each group ideated and described their design solutions. The following subsections provide detail about the experimental approach.

5.2 Creating the VR environment

The first step to assess the effects of embodied VR on engineering design was to create a virtual world based on a real-world case study. Cincinnati, Ohio, was mandated to address problems with their stormwater that was polluting local creeks and rivers. The neighborhood of South Fairmount in the Lick Run watershed was identified by the city as an area to redevelop to best address the stormwater issues in the city (Project Groundwork, 2012). Beyond barren lots and irreparable public amenities, stores, and homes, South Fairmount was home to the largest single-point emitter of combined sewer overflow (CSO) in the entire city of Cincinnati, discharging over 200 million gallons per year.

Two different "perspectives" were developed for the virtual world, while a control group received no VR intervention. Participants could enter the virtual world as either a human avatar or a bird avatar. The human and bird avatar were both navigated using handheld controllers. Toggles on the controllers were used to move their avatars around the South Fairmount neighborhood. The virtual world and the objectives in the virtual world were the same for both avatars.

The objective was a wayfinding exercise. Participants were asked to gather rings that were conspicuously placed throughout the South Fairmount neighborhood. To collect the rings, participants either used teleportation as the human controller or flew as the bird controller. This required the participant to experience the virtual setting in more detail than just walking through the site and increased the interactivity of the experiment (Markopoulos et al., 2015). Furthermore, this presented an element of gamification (Kim, 2014; Villagrasa et al., 2014), which was implemented to increase enjoyment and overall immersion.

In total, 102 civil engineering students were recruited for the study and randomly assigned to one of the three groups: control (n=33), human avatar (n=34), or bird avatar (n=35). The control group did not receive any virtual reality experience. The control group was provided with the case study details and two-dimensional drawings of the current area of interest in South Fairmount. Prior to the human and bird avatars experiencing the virtual world, students received a brief instructional course about how to operate an avatar in a virtual world.

The time spent in the virtual world was not limited but on average, participants in both groups spent 10-15 minutes collecting rings throughout South Fairmount. Longer immersion times can induce cybersickness (Cobb, 1999, p. 199; Giroux et al., 2013; Kourtesis et al., 2019; Martirosov & Kopeček, 2017; Murata & Miyoshi, 2000), but this was not experienced by any of the 69 participants in both VR groups.

5.3 Natural Language Processing and Thematic Content Analysis

Prior to receiving the case study information, all participants were asked to complete the Nature Connectedness Scale (Mayer & Frantz, 2004). Participants in all groups were asked to re-take the Nature Connectedness scale at the end of the experiment.

Following the VR experiment, participants were instructed to redesign the area of interest that was traversed in the virtual environment, focusing on minimizing CSO and improving the surrounding area. Participants spoke aloud and were recorded during this process. Audio files were transcribed and coded using both natural language processing (NLP) as well as Thematic content analysis (TCA).

NLP coding determined the semantic distance (how similar words are) of the transcripts. The Python package SpaCy was utilized for this. SpaCY work by measuring the semantic distance of pairs of words. Stop words were removed from the transcript and SpaCy compared each remaining word to every other word, determining the overall semantic similarity of the words utilized. The average semantic distance was used as a proxy for the “design space” explored by each participant (Vieira et al., 2022). The smaller the value the greater the distance between words and used as a measure for the size of the design space participants explored.

While NLP can be harnessed for its power in determining the breadth of the design space, thematic content analysis was used to understand which concepts within the design space were considered. The ideas presented in each transcript were coded based on their alignment to gray infrastructure, green infrastructure, or socioeconomic improvements by two independent coders.

6 RESULTS

6.1 Nature-relatedness

Embodiment through VR influenced design students’ perceived nature-relatedness. Students that embodied the bird avatar were significantly more likely to hold stronger nature-relatedness compared to the human avatar and control group (F = 0.44, $p < 0.0001$), with a small to medium effect size, after the virtual reality intervention. Furthermore, a t-test revealed that the students who embodied the bird avatar produced a significant increase in nature-relatedness within the group ($p = 0.013$, Cohen's D = 0.26). The effect size for each group is provided in Table 1.

Table 1: Nature-Relatedness Score Pre and Post Design Intervention

Group (n)	Pre-Score (STD)	Post-Score (STD)	% Difference (Pre-Post)	Cohen's D (group)
Control (33)	3.46 (0.37)	3.53 (0.31)	2.00%	0.46 (Bird); 0.19 (Human)
Human avatar (34)	3.53 (0.55)	3.62 (0.53)	2.52%	0.19 (Bird)
Bird avatar (35)	3.6 (0.45)	3.72 (0.47)	3.28%	-

6.2 Semantic distance

Embodied and self-reflected VR applications influenced the size of the design space that participants explored. Using SpaCy, a score was developed for each participant's transcript based on the similarity between words. A score closer to one suggests a small, homogeneous design space, whereas a score closer to zero reflects a design space that is larger and more heterogenous. Once scores were calculated for each participant, a one-way ANOVA test with a post-hoc Tukey HSD identified significant results between groups reported in Table 2.

Table 2: SpaCy semantic distance results

Group A	Group B	p	Means (Group A; Group B)
Bird avatar	Control	<0.001	(0.312; 0.321)
Bird avatar	Human avatar	<0.001	(0.312, 0.321)
Control	Human avatar	-	(0.321, 0.321)

6.3 Thematic Content Analysis

Embodiment and self-reflected VR also changed the thematic ideas of participants' designs. Each transcript was coded based on ideas for South Fairmount for three themes: gray-thinking stormwater infrastructure, green-thinking stormwater infrastructure, and socioeconomic improvements. While the number of ideas about gray or green infrastructure within these three groups was not significantly different, a Kruskal-Wallis with post-hoc Dunn tests revealed that the bird avatar (p=0.0079) and the human avatar (p=0.0002) included significantly more ideas for socioeconomic improvements to the neighborhood. Examples of socioeconomic improvements that were reflected in the transcripts include the addition of park space for public enjoyment, mixed-use retail centers, and new housing developments.

While no change was detected for gray and green infrastructure ideas *between* the three test groups, a within-group analysis of the ideas revealed significant differences for the bird group. The bird avatar significantly mentioned green ideas (p=0.001) and socioeconomic ideas (p=0.003) more than gray ideas. This differs from the previous analysis by grouping and testing the themes (gray, green, and socioeconomic) within each individual group. In other words, embodiment significantly impacts the amount of green and socioeconomic ideas that are provided in the conceptual design process.

7 DISCUSSION AND CONCLUSION

The research presented in this paper helps to expand the application of pro-environmental behaviors into the field of engineering design. Considering nature as a stakeholder through VR embodiment can foster a stronger connection between individuals and the environment, leading to more sustainable design ideas. The embodiment of a bird through VR also had an observed effect on nature-relatedness. These findings align with prior research (Ahn and Bailenson, 2012; Spanenberger et al., 2022; Soliman et al., 2017). Past experiments using VR embodiment found participants feeling more imminence with nature, which was used to help spur subsequent involvement with subsequent pro-environmental behaviors (Ahn & Bailenson, 2012; Ahn et al., 2016). The research presented in this paper extends these prior findings about pro-environmental behaviors into the engineering design of the built environment.

The analyses of the design space provide new evidence about the effects of embodiment on designers' cognition. Embodiment through VR expanded the words designers used to express and articulate their design ideas. This increase in design space exploration can be seen as an indication of a potential change in designers' empathy. As VR designers became more attuned to the experiences and perspectives of an embodied being, they were more likely to speak and act on behalf of the embodied entity, potentially demonstrating a heightened sense of empathy and consideration (Ahn & Bailenson, 2012; Kors et al., 2020). This expanded expressive capacity and increased empathy has the potential to inspire novel and sustainable design solutions that prioritize the well-being of both humans and the natural world, ultimately leading to more environmentally conscious design ideas.

The thematic content analysis provides additional insight into how embodiment through VR influences designers' cognition. The observation that both the bird and human VR groups mentioned socioeconomic benefits significantly more than the control group suggests that embodiment in VR may enhance designers' awareness of the broader social and economic implications of their design decisions. When designers engage with VR simulations that embody a bird or a human perspective, they are immersed in a virtual context that allows them to experience the environment from different vantage points. This experiential shift may help to broaden their understanding of the interconnectedness between the natural environment and socioeconomic factors (Bertram & Rehdanz, 2015; Casal-Campos et al., 2015). The immersive nature of VR experiences may help to evoke a sense of presence and realism, enabling designers to simulate and explore scenarios that involve socioeconomic considerations. By actively engaging with these scenarios, designers may develop a deeper appreciation for the socioeconomic dimensions of their design, prompting them to proactively integrate such considerations into their design thinking.

The implications of this research extend to benefiting the conceptual design process through the integration of embodied VR experiences. Beyond the expansion of the design space explored by participants, the embodiment of nature in VR leads to the generation of design ideas that prioritize both natural and societal benefits. This suggests that designers who engage with embodied VR experiences may exhibit a greater consideration for green infrastructure, sustainable practices, and socioeconomic aspects within their designs.

However, further research is needed to delve into the specific details and nuances of the green, gray, and socioeconomic ideas mentioned within the design ideas listed in their transcripts. By conducting more analyses of the design concepts expressed by participants, a more comprehensive understanding of the specific design elements and strategies associated with green infrastructure and socioeconomic considerations can be obtained. This deeper understanding will contribute to the refinement and optimization of the design process, enabling designers to create more sustainable, contextually appropriate, and socially inclusive solutions.

There are several notable limitations in this research that warrant consideration for future studies. One limitation is the use of engineering design students as participants rather than active professionals in the field. However, this sample was chosen because these students are already engaged in design roles early in their careers and will be part of design teams helping make these types of design decisions within months of graduation, making them a suitable group to examine the impact of embodied VR on their design thinking. Additionally, given the relatively early stages of incorporating embodied VR into land development and civil engineering, using VR as a tool can be beneficial for these students to gain experience and enhance their skills for their future professional careers.

Future studies building upon this research should focus on identifying the efficacy of embodied VR in terms of the quality of designs produced. While this research has revealed the influence of embodied VR on both nature-relatedness and design ideation, less is known about the overall quality of the designs generated through this approach. It would be valuable to investigate whether embodiment through VR has an impact on the sustainability of designs or the inclusion of sustainable features. This could be explored by assessing aspects such as energy efficiency, use of eco-friendly materials, or consideration of biodiversity. By addressing these limitations and exploring the impact of embodiment on design quality, future studies can further contribute to the current understanding of how embodied VR can be effectively utilized in the design process. Such investigations will help inform educational and professional practices, as well as guide the development and implementation of VR tools and techniques to promote sustainable and innovative design solutions.

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