Evaluating the Impact of Immersive Technology on Spatial Ability Development in Beginning Architecture Students

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This study investigates the pedagogical impact virtual reality (VR) has on design education for beginning architecture students by examining how VR affects spatial visualization skills (SVS) development. In order to examine the effects of VR, a pilot study was conducted in the Spring of 2018 to evaluate the training, experimental method, and testing procedures and instruments that could be used in a future study. We compared the SVS performance of eight 1st year architectures students who used VR to completed mental-rotation exercises with four 1st year architectures students who completed the same exercises sketching on paper.

The results indicated a correlation between intervention training and improvement from pretest to posttest, suggesting a change in mental rotation abilities. Participants using VR completed the exercises more successfully than the group sketching on paper. However, the paper-sketching group showed greater improvement in the pretest/posttest scores indicating spatial ability training, problem solving, and cognitive benefits experienced in an immersive environment might not translate to real-world situations. The goal of the exploratory study was to better understand the impact that VR might have on architecture design education through an evaluation of its direct effect on spatial visualization skills in beginning architecture students. The results of the study emphasize the need for adequate sample sizes and while the study did not yield statistically significant results, it does offer a suitable framework for future research to build on.

INTRODUCTION

In the last few years we have experienced a renewed interest in the implementation of immersive technology in numerous fields, with many professionals embracing it into their workflows. The learning environments of schools are not exempt from this trend.[1] Research findings suggest that in the race to bring this technology into the classroom, teachers might not take the time to question to what extent or whether it is beneficial to incorporate the technology.[2] Fowler believes that technology is often incorrectly used simply as a replacement, without exploring its unique characteristics, stating "one risk with high-fidelity 3D virtual learning environments is that they will be used to create virtual classrooms that 'feel' and look like real classrooms but lose the opportunity to create pedagogically new and innovative learning environments."[3] Additionally, Jenkinson observed that "For too long we have developed and lab-tested innovative e-learning tools, which are subsequently inserted into the classroom without an adequate understanding of the context in which the tool is used."[4]

Beneficial use of immersive technology in the education can be complicated by inadequate delivery, planning, and understanding. If educators are to understand how best to implement immersive technology, particularly in the field of design education where little research has been occurred,[5] a critical analysis of the strengths, limitations, and pedagogical impact of the technology must occur. This study attempts to redefine the manner in which virtual reality (VR) is used by architecture students by developing a new model of digital design education and research: a model that takes advantage of the capabilities of the medium, without limiting the design process or trivializing the new technology. As directly measuring VR's impact on design education is not easily quantified, it was necessary to identify a surrogate process to assess. As discussed in the following sections, spatial ability is an inherent component of design education and for that reason, this study used it as a surrogate to be measured when assessing VR's impact on architecture design education.

SPATIAL ABILITY AND DESIGN EDUCATION

Design education often incorporates applied practical exercises to teach and improve individual and combined spatial abilities of design students. Through the use of manually generated drawings and graphics, architecture students are taught how to visualize their design and effectively translate a mental image into a two-dimensional representation. This technique has proven to be an effective design tool that allows student to explore, analyze, and communicate their designs and it is this drawing activity that contributes to the design discovery process and formation of new ideas.[6] Purcell[7] discussed how the drawing process is more than a means of communication with others, it is an intrinsically part of the mental process which is central to design.

It has been proposed that the cognitive processes involved in drawing may be related to those associated with spatial visualization. In a study conducted by Samsudin, Rafi, and Hanif, students who received spatial visualization training also performed better in the study's multi-view orthographic drawing tasks.[8] The authors postulate that spatial visualization skills were essential to successfully completing visual-spatial tasks, such as orthographic and isometric drawing. It is through these drawings that architects can externalize and realize their design thoughts, which is critical for both the communication and generation of design.[9]

SPATIAL ABILITY

"Architecture is often considered a visual subject."[10] To successfully read, understand, and manipulate visual spatial information, architects are expected to have strong spatial ability.[11] The ability to visualize objects and situations in one's mind, and to manipulate those images, is a cognitive skill vital to many career fields. For architecture students, an important spatial ability is the capacity to generate three-dimensional knowledge from two-dimensional information. This skill requires the perceptual ability to interpret what is seen, and the spatial ability to mentally manipulate visual representations. Architecture students require this ability to think and design in 3D by drawing information from 2D representations.[12]

In a broader sense, spatial skills can be broken down into spatial visualization and spatial orientation, where visualization involves mentally moving an object and orientation is the ability to mentally move the viewpoint.[13] Spatial visualization is further split into two categories, as defined by McGee: mental rotation and mental transformation.[14] Mental rotation and mental transformation differ in that mental rotation manipulates the entire object while mental transformation deals with only part of the object is transformed.[15] Spatial orientation involves the ability to determine relationships between different objects and understand the body orientation of the observer in relation to external objects or stimuli.[16] Orientation in the domain of design education can best be understood in terms of scale approximation and comprehension, and such understanding is limited in students beginning their design education.[17]

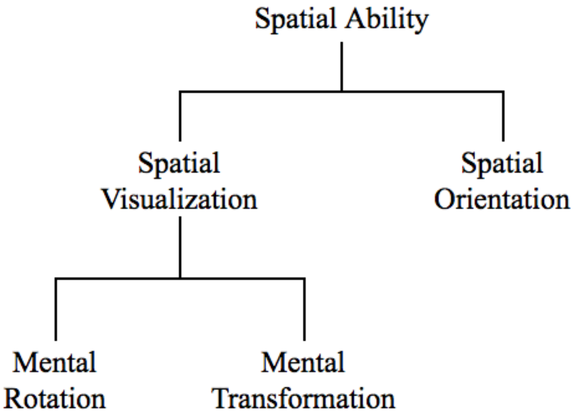

Figure 1. Classification of spatial skills (Sorby, 1999)

By receiving training focused on improving spatial abilities, students can achieve improved performance in architectural design by mastering the techniques of spatial visualization. As Roberts states in his research concerning predictors of future performance in architecture design education "A large part of architectural education is concerned with the development of new abilities, values, and conceptions, so that eventually students are able to think and act as architects, through creative thinking and the mental manipulation of space."[18] He further states, "It is also suspected that levels of visual and spatial perception may impact upon performance in architectural education."[19] Previous research that has looked at the impact virtual reality has on architecture design education has resulted in inconclusive or limited results.[20] This study attempts to further explore the procedures involved in such evaluation which will hopefully lead to a more thorough and detailed future study.

TRAINING

Spatial ability was originally regarded as an innate ability, fixed, and not susceptible to development. However, experimental studies have since established that this ability can be improved through focused training modules and lectures designed specifically to enhance this ability.[21] Sorby and Baartman demonstrated that engineering students enrolled in a spatial-visualization-skills training course made statistically significant gains on the average Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R) scores.[22] These students also went on to outperform those in the control group in subsequent graphics courses, had higher GPAs, and were more likely to remain in the engineering program.[23] Guven and Kosa evaluated the impact dynamic geometry software training had on mathematics students' spatial skills.[24] The results showed that, after 8 weeks of training, students exhibited significant improvement on the PSVT indicating improved cognitive abilities, specifically in the areas of mental rotation.[25]

The ability to improve spatial visualization skills through training was also evident in the experiment conducted by Samsudin et al. in which they evaluated the outcomes of mental rotation and spatial visualization technology-based training.[26] In their study, participants in one condition were given the ability to interact with animated training objects and navigate a virtual environment (VE), affording close-up and distant views of the training objects. The second condition, while still in a VE, limited the interaction for participants. The control condition involved similar spatial exercises using printed materials. Their findings showed that training resulted in significant gains in spatial visualization. Importantly, the study demonstrated that efficiency is dependent on the method of training since the technology-based experimental groups exhibited greater improvement.[27] Participants who were afforded the most interactivity and ability to manipulate objects in the VE showed the

Figure 2. Student creating and evaluating their design using VR

greatest spatial ability gains. The authors of the study postulate that it suggests an enhanced visual perception of objects in 3D space, indicating that participants effectively utilized these spatial cues to improve the cognitive processing necessary to solve the spatial tasks and it encouraged the active processing of information.

ARCHITECTURAL LEARNING

Studies have indicated that spatial abilities affect students' performance in design-related courses and that those spatial abilities can be improved through appropriate educational training. Experiments by Casakin have demonstrated the impact spatial manipulation, visualization, and drawing have on students' ability to successfully solve ill-structured problems.[28] The study demonstrated that architecture students with access to visual material outperformed their peers when solving ill-structured problems, suggesting such designers use mental processes to take existing imagery and meaningfully recombine them as part of the design process.[29] It is this operation of spatial transformation that leads to the mental synthesis necessary for design problem solving.[30]

Cho's study sought to explicate the correlation between spatial ability, creativity, and performance in architecture design studios. While her findings did not establish a correlation between participant scores from the Torrance Test of Creative Thinking (TTCT) and studio performance, they did show that studio performance correlates with the Architectural Spatial Ability Test (ASAT).[31] The ASAT is an architecture-domain specific test designed to measure the spatial visualization skills (SVS) of architecture students by evaluating their capacity to fluently transform 2D architecture information into 3D form and vice-versa.

Tversky, Schon, and Goldschmidt all agree that when formulating external representations, designers are engaged in spatial cognition process in which the representations serve as cognitive aids information processing, aiding designers in reasoning as they evolve in their interpretations and ideas for design solutions.[32]

VR IN ARCHITECTURE

Goldschmidt states that "Sketching is beneficial because it supports visual thinking.[33] Visual thinking is a preferred cognitive strategy in design because it is useful to work with visual representations when endeavoring to arrive at the creation of a tangible entity that must by definition have distinct spatial/visual properties." Sketching as an exploratory process in design is customary. It allows designers to experiment with new ideas and search for design concepts through an established system of visual stimuli. While the introduction of VR and immersive design tools in architecture brings new 3D sketching tools, there is little research in this area, specifically its impact on education and the learning process.[34] Sketching in the technology area often means moving to modeling and technical Computer-Aided Design (CAD) drawing. Sketching in VR could offer the ability to visually represent depth in three axes. This additional information, from an egocentric perspective, could potentially add another layer to how designers think.[35] The role that emerging VR technology and design software has in architecture education is another question that this study will address.

It has been demonstrated that training in VR can transfer to real world learning, performance, and demonstration of spatial navigation.[36] "Users in virtual worlds can act on the objects in the 3-D environment, which allows them to learn by doing, to observe the outcomes of their actions, to test their hypotheses about the world and to reflect further on their own understanding."[37] Mikropoulos states that "these worlds provide users with experiences they would otherwise not be able to experience in the physical world and leads to the attainment of specific learning outcomes."[38] Conversely, many believe that while research has demonstrated the possible benefits VR might have when applied to the design process, this technology has yet to be fully incorporated into architecture design education.[39] While the technology has been around in various forms for decades, architecture professors are still not using VR to its potential.[40]

Since its inception decades ago, Mikropoulos maintains that VR has matured into a technology which is now appropriate for pedagogical use. This is particularly true in the fields of science, design, engineering, and mathematics, where teaching and learning incorporates issues that are mainly concerned with information and knowledge organization, spatial perception and orientation, and visual perception.[41] The field of engineering education, for example, has continued to move forward with research on how spatial abilities can be developed and improved using VR technology.[42]

EXPERIMENTAL PROCESS

In the Spring of 2018, I conducted a pilot study in order to better understand the potential of VR 3D sketching as a training tool for improving spatial ability. The pilot evaluated the training, experimental method, and testing procedures and instruments that will be used in this proposed study. The goal was to see if there was any indication that a transfer of learning was occurring, specifically what impact SVS training in an immersive environment would have on SVS tasks in other situations. For this study, the Google-developed application Tilt Brush, was selected for its intuitive interface, ability to sketch in three dimensions, and low learning curve. Using Tilt Brush with an HTC VIVE headset, the aim was to understand how the activity of sketching a design is impacted by the addition of a third dimension that immerses and embodies the designer. I expected that the added immersive aspect of using the HTC VIVE headset would improve the designer's ability to think spatially, particularly when involving mental rotation, presenting a new way to consider training designers in developing and improving design abilities. The study hypothesis was that compared to traditional paper sketching, the added embodiment and ego-centric perspective of Tilt Brush in the HTC VIVE would improve designers' spatial abilities. To test this hypothesis, paper sketching was compared to VR 3D sketching, with a pretest-posttest design that used the Purdue Spatial Visualization Rotation Test.

MEASUREMENT

The PSVT:R[43] was administered to the sample group prior to training and immediately after in order to assess the impact of using digital tools in immersive environments,. This instrument was used to measure performance in aptitude and evaluate improvement. In addition to standardized tests, observations of task procedure during the experiment, questionnaires, and post intervention semi-structured interviews regarding ease-of-use were utilized to better understand the impact of an immersive technology intervention in architectural design education. These tasks functioned both as part of the spatial learning process typically taught in design studios and to evaluate the effect of VR on that process.

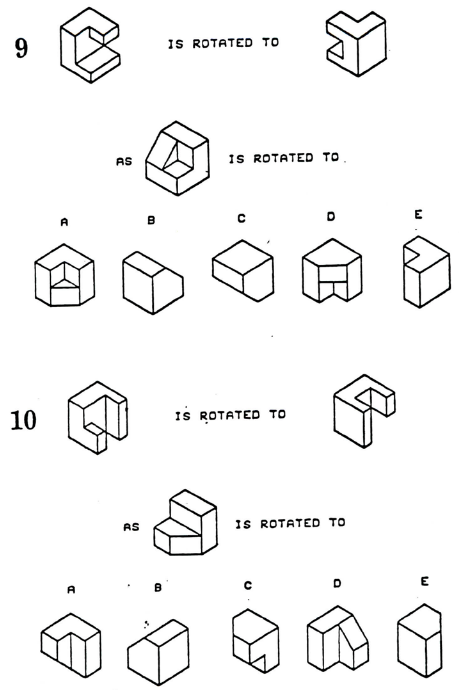

Figure 3. Example of PSVT:R Question (Guay, 1976)

The PSVT:R test, while not contemporary, has been studied and used by researchers for more than 30 years and its reliability and validity is well documented in literature.[44]

PARTICIPANTS

The population that this study focuses on is undergraduate architecture students, particularly those in design-foundation studios. Data was collected from 1st year architecture students who were randomly assigned to treatment conditions. The individual, rather the classroom, was the unit of analysis. It is well established that gender plays a significant role in spatial skills and females often score lower on spatial ability tests.[45] Accordingly, care was taken to balance the numbers of male and female participants in the test groups. Participation in the study was open to students in the Department of Architecture who were in their first year of study.

PROCEDURE

Following consent, I explained that the mental-rotation exercise is not a test, but would provide insight as to how well the sketching exercise could help students. The exercise was then

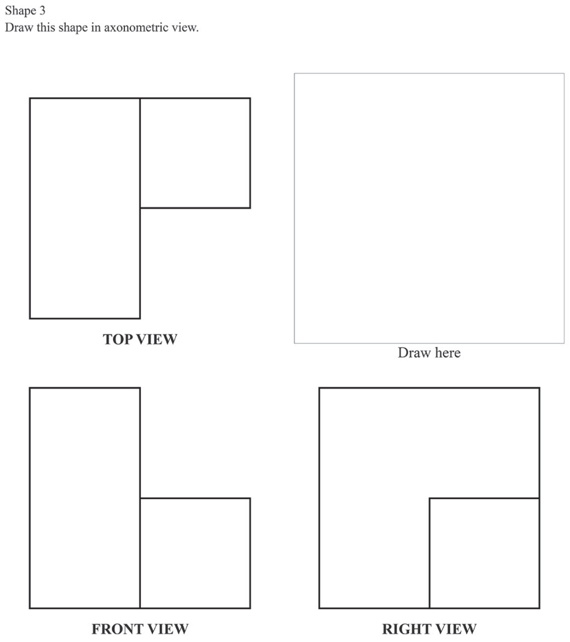

Figure 4. Example of Isometric Drawing

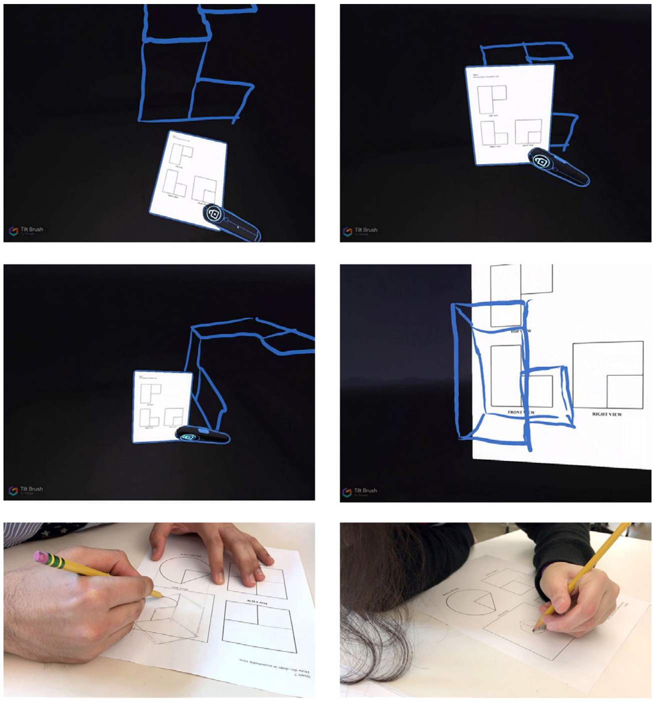

Figure 5. VR Environment manipulation to solve drawing tasks and manual reconstruction of 3D by 2D mapping onto a cube

administered. After completion of the mental-rotation exercise, a short training exercise was provided, either using Tilt Brush or sketching on paper. For subjects in the HTC VIVE group, the headset and two hand controls were introduced and explained, showing how to wear the headset and adjust the fitting using the adjustable knob. After a few minutes of practicing, the researchers confirmed with the subjects that they were comfortable using the controls. The exercise file within Tilt Brush contained a single shape broken into top view, front view, and right view, similar to the sheet of paper for the paper drawing group. Participants were given 3 minutes to draw the shape in isometric perspective, a skill taught and well known in design education (see Figure 4). This process for both the paper group and HTC VIVE group continued for 10 different shapes for a total of 30 minutes. Following the sketching exercise, participants were asked to fill in another mental-rotation exercise. After completing the exercise, students completed a short exit survey about their experience with their sketching medium.

RESULTS

Initial findings indicate a correlation between intervention training and improvement from pretest to posttest, implying a change in mental rotation abilities. When completing the isometric drawing task, HTC VIVE participants scored higher than participants in the paper drawing group. This result could suggest that the added embodiment and ego-centric perspective of the immersive environment improved the participants spatial abilities; however, another possible explanation is that the technology allowed participants to solve the task in ways unique to VR. Within Tilt Brush, participants were allowed to manipulate the position, rotation, and scale of the drawing task sheet. Many took advantage of this opportunity as a means to construct the 3D object necessary for the successful completion of the task (see Figure 5 screen capture). Tilt Brush could have facilitated the task by allowing the participants to offload the cognitive process of mental rotation to the computer and software being used.

Participants who completed the paper drawing were not directly afforded a similar process, suggesting that the process of mental rotation and translation to isometric representation was completed mentally. However, some attempted to perform the reconstruction process on paper by manually mapping the three 2D views to an isometric cube and use this as a guide to reconstruct the 3D object (see Figure 5 photos).

As mentioned previously, these additional opportunities for manipulation in immersive environments could possibly lead to greater task success for participants in the HTC VIVE condition. This was an expected outcome, however, the results of the pretest and posttest showed results that are contrary to our hypothesis. Participants paper drawing demonstrated greater improvement than those in the HTC VIVE (see Table 1). This suggests that spatial ability training and the problem solving and cognitive benefits experienced in an immersive environment might not translate to real-world situations, thus a transfer of learning did not occur in this specific situation. Conversely, participants who experienced spatial ability training using traditional processes, seemed to retain that knowledge and could then apply it in external situations.

DISCUSSION

The main objective of the present study was to examine whether the use of VR improved students' ability to solve tasks focused on mental rotation. This study did not show clear evidence of the effectiveness of VR as a tool for improving mental rotation ability in beginning architecture students. Almost all participants improved their scores in the PSVT:R posttest. In fact, students in the control group showed a slightly greater degree of improvement on mental-rotation posttest measurement.

Conversely, the study indicated that students who used VR were marginally more successfully in solving mental-rotation problems. One possible reason for this could be that students felt that VR reality afforded them a new mechanism that aided problem solving. This was indicated by several participants in the exit survey.

> "It is a very useful method of drawing in 3D in actual 3 dimension, it will make the process of conveying ideas which require visualization very useful, especially for the people who are not that great in visualization."
>
> "At one point I crouched under the square that I drew to see if I drew it somewhat accurately in 3D."
>
> "Being able to move around in a drawing, especially being able to get so close to it, was so helpful."
>
> "It is better to visualize drawings in 3-D and be able to move around structures, it makes the shapes easier to understand."

These participants were describing the immersion they felt in VR and on how helpful it was in completing the drawing tasks. This sense of immersion or presence provided by virtual environment is of major importance to the learning process. Winn and Windschitl[46] believe that this occurs because presence enhances first-hand experiences and "first-person psychological activity occurs when people interact directly with worlds, whether real or virtual." Many of the factors that appear to affect presence are known to enhance learning and performance. Witmer and Singer argued that meaningfulness and coherence of a stimulus set promotes learning.[47] In their 1996 study, Witmer, Bailey, and Knerr showed that virtual environments could be an effective tool for training route knowledge when participants experienced a high level of presence and presence was associated with better performance. Witmer et al. concluded that "VEs increase presence by allowing users to interact more naturally and directly with the simulated environment, by immersing users so that they perceive they are inside the virtual space, and by minimizing outside distractions; consequently this strong sense of "being there" should also improve learning.[48]

ID	Condition	Pretest Score (out of 10)	Drawing Score (out of 10)	Posttest Score (out of 10)
1	t	9	9	9
2	p	4	7	6
3	t	6	5	5
4	t	9	10	8
5	p	7	10	6
6	t	10	9	10
7	t	5	4	5
8	t	9	9	9
9	p	7	5	7
10	p	4	6	6
11	t	10	10	9
12	t	5	8	9

TiltBrush average	7.875	8	8
Paper Average	5.5	7	6.25

Table 1: Pilot Study Results

Another possibility is that the novelty or "coolness" factor of VR kept student engaged, interested, and motivated during the experiment, leading to more successful results in the required tasks. Again, this was indicated by comments made by the students.

> "The vr sketching exercise was very cool."
>
> "It was incredible, didn't know technology like this existed"
>
> "It was great. fun! I enjoyed it and will even more so I think outside of an experiment."
>
> "The VR exercise was 'an elite experience.'"

As discussed by Dalgarno and Lee, motivation and engagement are two of the intrinsic learning affordances of virtual environments, emerging from the ability of the learner to make personal choices while completing tasks in such environments.[49] In a broader sense, intrinsic motivational factors, such as task interest or the enjoyment of effort, affect the processes that have been shown to influence how well students deploy their existing skills and knowledge, how well they acquire new skills and knowledge, and how well they transfer these new skills and knowledge to other situations.[50]

CONCLUSION

This paper describes an exploratory study whose goal was to better understand the impact that VR might have on architecture design education through an evaluation of its direct effect on spatial visualization skills in beginning architecture students. The primary limitation of this study was that the sample size was less than adequate to draw statistically relevant conclusions. The short duration provided for students to learn in the virtual environment was also less than ideal. It is expected that a more conclusive outcome would result from longer training in VR and additional learning tasks for students to complete.

This attempt to establish a causal relationship between learning spatial visualization skills in VR and improved spatial ability in external conditions did not yield concrete results; however, it offered a framework for future, more rigorous research to build on. By investigating the impact VR has on visualization training, we can better understand the factors involved when using VR in the course of architectural education. Most importantly, it is hoped that this understanding will lead to a more effective use of educational VR technology, allowing students to better understand spatial qualities by equating relationships between body and environment, ultimately resulting in better design.

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