The Design & Development of an Immersive Learning System for Spatial Analysis and Visual Cognition

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1. INTRODUCTION

1.1 Purpose

Spatial thinking is based on three elements: concepts of space, tools of representation, and processes of reasoning, (Council, 2006); and, although students and professionals in the architecture industry rely on spatial thinking to develop and simulate the final design solution, the tools of representation involved are noticeably limited to the two-dimensions viewable on a traditional computer monitor or sheet of paper. Therefore, an immersive cohabitation of the designer within their detailed and complex model – at full-scale, in three dimensions – would better support and augment spatial thinking by allowing designers to both conceptualize and reason volumetrically. Fortunately, there are now low-cost tools that provide a means for virtual cohabitation and improved spatial thinking.

Specifically, proliferation of increasingly affordable virtual reality hardware and the accessibility of development software traditionally reserved for video games has resulted in the emergence of a new platform for teaching and learning about the design of volumetrically complex spaces: the Oklahoma Virtual Academic Laboratory (OVAL). The OVAL system users to collaboratively manipulate and analyze 3D assets across a network of Head Mounted Displays (or HMDs), like the Oculus Rift. With the creation of this system, design faculty at the University of Oklahoma are provided the means to create first-hand learning experiences in "full-scale" immersive architectural environments; environments that are typically only possible to study at full-scale post construction.

Use of this combined hardware/software system with highly detailed and accurate computer generated architectural models can provide designers with a completely immersive visualization whereby they can advance their spatial thinking skills while developing, analyzing and sharing architectural environments before they are actually built. This paper will explore the development and implementation of the OVAL platform, the experiences of the students and faculty using the OVAL platform, and the impacts implementing full-scale immersive visualization experiences had on the students design process and the design solutions they developed.

1.2 Literature Review

The general benefits of 3D visualization are well documented in the STEM fields, where NASA researchers (for example) are touting the capacity for such representations to help "reveal important, previously unknown [information]", which – in the case of architectural design – might relate to previously obscured clearances; accessibility issues; and furniture layouts etc. (Madura et al., 2015). Beyond advanced visualization, the OVAL platform, alongside the next-generation of VR-centered visualization tools, is providing students the means to explore existing but *physically distant*, but architecturally relevant, sites (Trautner, 2015). 3D scans of critically important designs, then, can be preserved inhabited regardless of the students' access to the physical location or indeed even their continued existence as is the case with the Syrian Heritage Project who are 3D scanning artifacts threatened by conflict in the Middle East. Finally, the literature concerning serendipitous information retrieval (De Bruijn & Spence, 2008) suggests that even very short (~100ms) instances of visual stimuli can generate solutions to environmental problems. Given the OVAL system provides 360-degrees of interactive content to the user, the opportunity for to perceive spatial information relevant to design is likewise increased.

An interior designer's ability to visualize space is one of the main skills used to solve design problems associated with their projects (Guerlin & Nussbaumer, 2000). The design process requires interior designers to utilize visualization skills in order to work through, evaluate, and build upon their various solutions to the design problem. In order to effectively evaluate solutions to these problems, designers must be able to accurately visualize these solutions simultaneously. Design solutions are typically sketched or drafted in two-dimensional forms, or modeled in three-dimensional forms. Although the design of the spaces can be analyzed and revised with these graphic methods, graphic representations do not provide a full scale spatial environment to experience. Scaled representations require the student to imagine themselves looking around and moving about the space within the drawing or model. This process is susceptible to mistakes in spatial perceptions because of the required changes in scale (Henry & Furness, 1993).

People are generally quite good in experiencing real spaces and experimenting with the spatial relationship between real objects in that space; however, people often possess only a small inherent understanding of the true size of space in an abstract or unfamiliar form (Hinkley, Pausch, Goble, Kassell, 1994). People do not innately comprehend spatial visualizations as well as they experience them. "It is necessary to be able to estimate sizes and distances fairly accurately, and also be able to visualize what a complicated interior might look like from various viewpoints" (Zavotka, 1986, p. 46). The ability to visualize is essential for problem solving in interior design and, because of this, interior design students must learn visualization skills (Guerin & Nussbaumer, 2000). In educating design students, it is important to provide experiences that simulate the real scale design solutions that they are developing and are learning to communicate graphically. "The closer the simulation is to the actual environment, the less mental visualization ability is needed by the students" (Fowles & Skjelver, 1976, p.46).

The built environment disciplines of architecture and interior design provide excellent applications for virtual environments. Interactive virtual models that simulate full-scale forms, materials, and light in an integrated spatial context provide a experiential context for the communication of design solutions (Hemmerling, 2008). Immersive environments can provide a setting that expands the support and analysis capabilities conventionally available digital design tools can provide during the design process while also providing enhanced perceptual engagement in support of spatial design decision making (Angulo, 2013).

2. METHODS

2.1 Participants and Context

An exploratory study was conducted with undergraduate students (11 female, 2 male) enrolled in the senior level Interior Design Capstone course in the College of Architecture at the University of Oklahoma. This study was aligned with the 5 credit hour Capstone project in the Interior Design Capstone Studio taken during the final semester of the student's academic career. Students undertake a project of significant scale and complexity, each developing and defining the scope of their own project. Projects are multi-level, a minimum of 30,000 square feet, and are mixed-use with a combination of at least three different programmatic focuses. Mixed-use project types include hospitality, corporate, healthcare, residential, institutional, and exhibition space. The projects incorporate project identification, site and building analysis, research, programming, concept development, space planning, schematic design, design development, furniture and finish selection, lighting design, three-dimensional exploration and modeling, and detailing. The project deliverables include a specifications, construction drawings and rendered presentation drawings. Faculty provide ongoing critique and guidance throughout the semester. There are weekly reviews throughout the semester and every student is required to participate in each review session.

2.2 Systems

This OVAL system comprises both a hardware and software elements. The railed chair, which provides range of motion and cable management, was custom-designed by the University of Oklahoma's physics fabrication lab. Discussions surrounding design of the railed chair centered on usability feedback gathered during an earlier proof of concept phase, where users were inadvertently striking their monitor or desk or keyboard, limiting engagement with the virtual environment.

We assembled two high-end gaming PCs to accommodate the technical requirements associated with moving millions of polygons in the span of time it takes for someone to turn their head. The primary criterion in building these machines, besides the graphical requirements, was low form factor, so the towers could fit below/behind the OVAL user. Off-the-shelf PC *peripherals* were also pivotal to the OVAL's hardware implementation. Those peripherals include a 3D Mouse (3dconnexion's *Space Navigator*), which, unlike a traditional mouse, is able to control motion along a vertical, z-axis; the LeapMotion hand tracker for preserving fingers and forearms in virtual reality; and the Oculus Rift Development Kit 2, the head mounted display (e.g. VR goggles) central to the immersive virtual reality experience.

These hardware components were combined on the software side of the OVAL implementation using the Unity3D gaming engine, which itself is available at no cost for amateur developers and for a relatively small licensing fee if distribution of software is planned. The executable application - presently in a .4 beta stage - combines the software "packages" that power the abovementioned off-the-shelf peripherals with a library of custom scripted interface elements to allow for shared manipulation and analysis of an arbitrary set of 3D assets across a network of head mounted displays. The LeapMotion hand tracker will recreate the user's hand movement in a virtual environment, for example, but it won't automatically trigger interactive commands pertaining to model conditions like scale and orientation, thus necessitating the development of custom C# code written in Unity's IDE (Integrated Development Environment), MonoDevelop.

Finally, by integrating networking software into OVAL, a shared VR experience can occur rmotely, and all changes made on a master workstation—including scale, rotation, lighting, and background imagery—are immediately transmitted to all co-participants, regardless of their physical location. In a classroom environment, this means that students automatically see what the teacher sees or changes. . To facilitate such a network, all 3D models are uploaded via a public-facing Dropbox directory, which immediately syncs with all OVAL clients, and allows any single client to pull in any uploaded model almost instantaneously. At its core, this hardware/software combo is actually a set of free or low cost video gaming components implemented with ergonomic foresight and a customized interface. Everything from the software behind the onscreen virtual buttons to the Oculus headset itself was designed for game development and the resulting price tag means that academic institutions are able to deploy the OVAL platform at a small fraction of the cost associated CAVE systems installed throughout the 90's and 2000's.

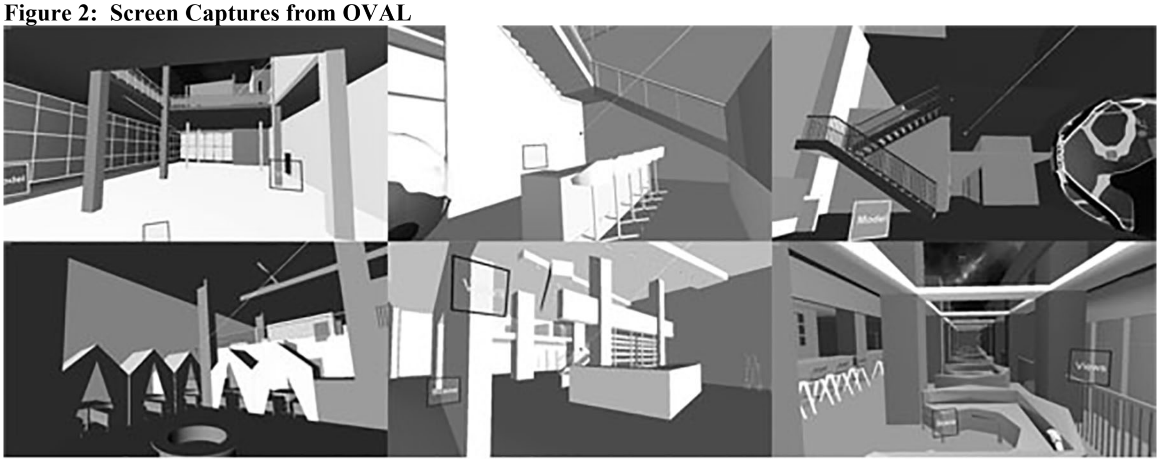
2.3 Procedures

Senior interior design students were recruited and volunteered to participate in two online surveys during the study. The first survey was completed prior to the students having ever used the OVAL system. The second survey was completed after the students had used system extensively. Students utilized the OVAL platform throughout the semester to experience and analyze the design solutions being developed (Figure 1). Student teams of three met for critique sessions with their studio professor held in the immersive full-scale environments simulated with the OVAL system. The first sessions began with an analysis of the existing spatial conditions (core and shell) of the buildings with additional sessions continuing on through schematic and design development stages of the project. The student presenting their project development acted as the "driver" within the OVAL platform while one other student and the professor were able to simultaneously experience, study, analyze, and provide feedback about the design during the critique sessions. Participants not fully immersed in the environment could still view the experience of the other participants from a nearby large screen. Students also used the OVAL system individually and without supervision from the professor throughout the semester to study the development of their designs and the spatial impacts of the decisions being made.

Figure 1: Students Using OVAL system

Throughout the course of the semester, students were also required to submit narrative summaries and screen captures of their experiences - using the output functions built into the OVAL system - and the analysis of their design project development with their weekly project review drawings and documentation. During each critique session held using the OVAL system, students were able to screen capture the immersive view of their model. These screen captures typically were taken during times within the immersive experience when something was recognized with their design that needed further development or when something was recognized as being successfully or unsuccessfully implemented into their design (Figure 2). One of the team members who was not fully immersed in the model with the OVAL system would take notes for the team member whose model was currently being analyzed. Screen captures along with explanatory narratives of the immersive experience and the design analysis were submitted to the professor after each session.

Figure 2: Screen Captures from OVAL



3. RESULTS

3.1 Summary of Results

After using the OVAL system throughout the semester, the majority of the students expressed that it greatly helped them to understand the impact of their design solutions on volumetric space. Although initially the majority of the students thought that use of the system would improve their understanding, final results showed a 31% increase, from 31% to 62% in the number of students who felt it greatly improved their understanding of the impact of their design solutions on volumetric space (Figure 3). Conversely, after using the system, students did not feel that it helped improve the creativity or spatial complexity of their design solutions even though they initially thought it would improve them (Figure 4). The majority of the students felt that use of the OVAL system would greatly help them to explain their design to others. This number increased after use of the system, showing in the end that almost all students thought it would help them explain their design to others (Figure 5).

Figure 3:

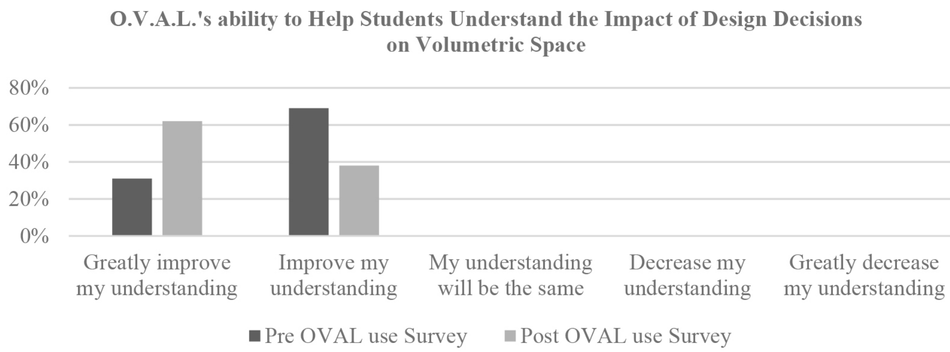


Figure 4:

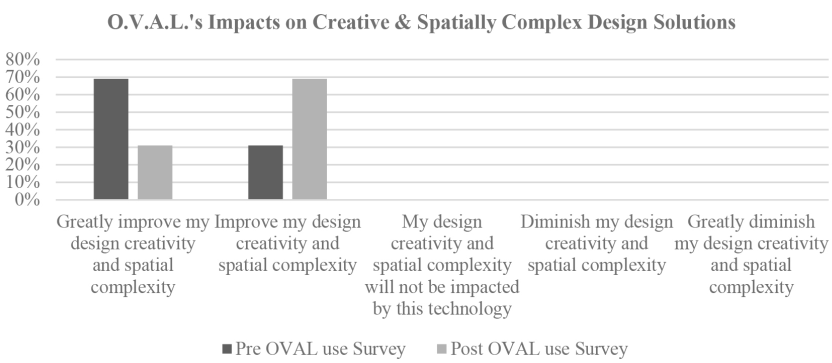
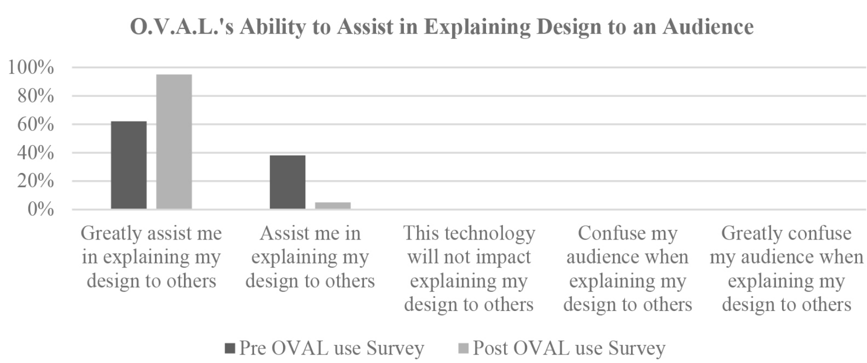


Figure 5:



During the sessions when the students were using the OVAL system throughout the semester there were several spatial issues that were continually identified through the narratives provided by the students. Ceiling heights were indicated as being higher than anticipated many times. Students also indicated continually that certain spaces were larger than had been expected. One student noted, "this experience of the restaurant made me more aware of how much bigger the dining area is than I had expected it to be and how open the circulation spaces are." Another student noted, "the retail space was much larger than anticipated and it was much more dramatic that I thought it would be. The yoga studio reception area was much more expansive than I initially wanted. After more analysis of the yoga studio using the OVAL system, I decided that I really liked the experience of openness and relief the expansive space in the reception area provided and the way it contrasted from the experience of the more intimate and private studio setting." Students also gave many comments indicating that spaces were much smaller than they had expected. Some of the comments from students included, "the circulation spaces were much smaller and more crowded than I had envisioned" and "the lobby space was not as deep as I had expected and will need to be increased in size in order to function properly".

There was a lot of emphasis on using the system to analyze the feasibility of space layouts throughout the sessions. Students noted how the system "really helped me realized problems that I was not catching in the floor plans or in the perspective camera views of my model" and how "traveling through my model helped me identify areas that did not function correctly as well as spaces that didn't evoke the reaction I was wanting to correlate with my design concept". One student commented, "I definitely feel that I learned more about my spatial design and understood the successes and failures much better than by just looking at the regular camera views taken from my model on the computer screen".

Students were also reassured that their design decisions would function as intended after using the system to experience their designs. Some of the students comments that support this reassurance included, "it was great to see how some of the unique shapes and forms I was beginning to integrate into my ceiling plane and walls were going to actually look and how they were going to impact the space and the reaction I was hoping to get from the occupants. Another student commented, "OVAL helped me compare some of my ideas for creating a more dynamic and rhythmic space while also considering the presence of light and how it could reinforce the forms I was integrating into the room".

There were many positive impacts relating to spatial understanding; however, the human body did not always have a positive experience when utilizing the OVAL system. Many of the students experienced motion sickness at various times throughout the semester. Some students experienced motion sickness within five minutes of use of the system, some not until thirty minutes or longer. Faculty typically spent more time in the immersive environments during class while critiquing several students' projects in one session. Extended periods of use for several hours in the system lead to some dire experiences with motion sickness. There were also several students who were not impacted by motion sickness at all. User interface modifications were made throughout the study to help control movement. Although these changes reduced motion sickness, many system users still experienced nausea.

3.2 System Summary

Several issues related to system use came to light during the course of the semester. More complex models naturally correspond to increased file sizes, which the OVAL system struggled to adequately process during the later portions of the semester. Not every student's experience was negatively affected as a result of file size, however. We learned that 200 MB is an approximately upper-limit to the .OBJ model file that can be comfortably experienced in virtual reality given our combination of hardware and software. Towards the end of the semester, a handful of student models had to be broken apart into several smaller models as well as "decimated" (e.g. geometrically simplified, which is required for curved surfaces in particular) to accommodate this graphics-processing budget. As the GeForce 980 card installed in the OVAL PCs now falls at the lower end of the market, and more powerful GPUs continue to come online, it's clear that such limitations are not hard and fast.

Motion sickness, as described above, is the dreaded result of sub-standard graphics hardware coupled with overly large model sizes, and more sensitive OVAL users were unable to re-engage with the system after they had been stricken. We noticed quite early that many instances of motion sickness occurred primarily in conjunction with a handful of unnatural maneuvers associated with movement in a three dimensional virtual space in the absence of gravity. The 3D mouse axis of motion corresponding to an airplane's *roll* axis was particularly nausea inducing, which precipitated the disabling of that particularly control vector for all future class sessions. Movement in early class sessions allowed for unnatural *speed* in all directions. Since movement speed proportionally linked to occurance of simulator sickness, this was a mistake (Kennedy, Stanney, & Dunlap, 2000). After disabling the roll axis and turning down the movement speed to simulate "human locomotion speeds", we noticed a marked decrease in instances of motion sickness (Oculus, 2016).

4. DISCUSSION AND IMPLICATIONS

4.1 Study Limitations

Limitations of this study include its small sample size from a single institution, which may have influenced the results. Not only were the participants from a single institution, they were from a single college from one university. Another limitation of this study was its restriction to senior level students only whose spatial skills may be influenced by the number of academic and professional experiences.

There are limitations associated with the small number of OVAL workstations at our disposal during this proof-of-concept phase. Meta-analysis indicates that an optimal size for small group learning effectiveness is four students (Kalaian & Kasim). Our groups also averaged four students, which means two students were disengaged from the learning experience, despite the fact that there is no technical limitation on the number of participants that can inhabit the OVAL (assuming they have the right combination of hardware and software at their disposal). Fortunately, recent developments mean that future courses and instructional sessions will only improve. Since the conclusion of the Spring 2016 semester, and the interior design capstone class described here, both the University of Oklahoma Law School and the new interdisciplinary makerspace, the Innovation Hub, have initiated the OVAL installation process. While these installations are not Architecture College oriented, the networked nature of the OVAL platform means that a large group of users can participate in virtual reality sessions regardless of their physical location. This is particularly important in the case of the Innovation Hub, which is located on the University's South Campus, out of easy walking distance for most undergraduates. There, faculty, researchers, and private sector businesses will be able to access a complete, 4-person OVAL system and guide library-based users from a distance, using built-in voice chat to streamline communication.

4.2 Instructional Implications

The use of virtual reality systems can support instruction focused on spatial reasoning. Numerous highly sophisticated architectural computer models are available from online sources for use by instructors and students, some of which replicate famous architectural buildings and landmarks. These models can be used to study and fully experience the spatial conditions of existing, proposed or fictional projects. Complex computer modeling skills for graphic design simulation and communication are now developed fairly early in the academic careers of design students. Students at any level in a design program who are creating these models can use virtual reality systems to augment their spatial analysis during a design project. Communication between disciplines of the built environment both academically and professionally is constant. Advanced methods of simulation, like the OVAL system provides, can also contribute in aiding in the communication and sharing of information between disciplines, helping to facilitate collaboration.

4.3 Partnerships

University of Oklahoma Libraries views itself as the crossroads of the University, but up until recently outreach – to other departments and colleges beyond the walls of the library itself – has been limited. This partnership, between OU Libraries and the College of Architecture, represents a real turning point in interdepartmental collaboration. Not only were spaces and technology shared between departments in this case, but the resulting usage data were instrumental in securing the expansion of the OVAL platform well beyond either contributing party's domain. As these tools continue to evolve, so too will collaborative outputs. Already peer-reviewed articles are in the works; international conference presentations have been accepted and scheduled, and curriculum additions across half a dozen unique colleges have been implemented. The OVAL system, then, will ultimately benefit not just the students whose spatial thinking skills have been improved as a result of its use, but it will also strengthen collaborative scholarship across the University.

5. CONCLUSIONS

Spatial thinking skills can be further developed and enhanced by combining computer generated architectural models with completely immersive visualization experiences. While proposed architectural environments are typically only available for full-scale spatial analysis after they are actually built, the use of this combined hardware/software system with the highly detailed and accurate computer generated architectural models enables analysis to occur throughout the design process. Although virtual reality experiences do not seem to impact the level of creativity or spatial complexity of design solutions, the use of virtual reality systems do have the ability to greatly impact a student's understanding of their design decisions on volumetric space. By providing full-scale simulated experiences to test design ideas, these systems can help students determine if their design solutions will spatially function.

Importantly, there are a handful software development firms offering early-stage tools that will allow future generations of students to not only view and analyze architectural designs, but to *construct* in virtual reality as well. Arch Virtual, Solarix, Sixense, and even Google (with the Tiltbrush application) have all demonstrated – to some extent – functionality whereby users can modify textures; add components; create primitives; and even *sculpt* in a virtual reality environment. Such features will be closely monitored and gradually implemented, alongside such planned improvements as voice chat (to support remote collaboration) and mobile-based OVAL versions.

Virtual reality systems, like the OVAL platform, can greatly assist designers in explaining their design solutions to others by providing more realistic spatial experiences. Impacts include communication between designers, between students or professionals in the built environment disciplines and also between designers and clients. Use of this technology is also making its way into design firms primarily as an alternative method of communication for clients. Students who are able to utilize and understand the advantages of these virtual reality systems during their academic careers have a competitive advantage for future employment.

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