VIRTUAL ENVIRONMENTS, RENDERED REALISM AND THEIR EFFECTS ON SPATIAL MEMORY

STEPHEN LEKAN

A THESIS
SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTERS OF SCIENCE IN ARCHITECTURE

UNIVERSITY OF WASHINGTON
2016

COMMITEE:
BRIAN R. JOHNSON
ALEX T. ANDERSON

PROGRAM AUTHORIZED TO OFFER DEGREE:
ARCHITECTURE

UNIVERSITY OF WASHINGTON

ABSTRACT

VIRTUAL ENVIRONMENTS, RENDERED REALISM AND THEIR EFFECTS ON SPATIAL MEMORY

STEPHEN LEKAN

CHAIR OF THE SUPERVISORY COMMITTEE:

PROFESSOR BRIAN JOHNSON
ARCHITECTURE

This thesis study is designed to document the process and analyze the results of a study conducted to determine the relationship between realism in rendering and the user's spatial memory of the space which was experienced when in virtual reality. This study is being developed in order to better establish virtual reality as a representational tool for architects when describing their design ideas to clients. Virtual reality, as a relatively new technology to the architectural profession, has relied on its ability to surprise and wow its audience, but as virtual reality becomes more ubiquitous and less novel, how and when does it become most effective? This thesis is designed to investigate one aspect of virtual reality, the realism of the environment, and draw conclusions based on that study. The study is conducted using the Oculus Rift Development Kit 2 (DK2) and takes the user through three separate realism levels of the same space and then tests their memory of each environment. Their results are then used to determine their level of spatial retention of each experience giving the researchers an idea of how their comprehension of the space was affected by the level of detail present in the environment. All three virtual environments are of the same space with the realism of the enviroment being the only factor manipulated. This study is being conducted to determine how and when the use of virtual reality as a representational tool in architecture yields the greatest psychological benefits for the potential clients and designers who utilize the tool. It is our theory that the higher levels of realism will yield higher impact to spatial memory. Due to constraints in time and subject pool this study is being developed as an outline or initial investigation that is designed to be expanded into a larger scale study in the future.

LIST OF FIGURES

Introduction

To an architect the most crucial element of any architectural presentation, is the ability for the designers to effectively and comprehensively convey their idea to their clients. The integrity and often the success of a design hinges on the client being able to accurately assess and develop a clear picture of what is being presented. The methods of representation that have traditionally been used for this purpose, such as the plans and sections, are often abstract making them difficult to understand without a background in developing and reading the projections used in architectural drawing. Models and more correlative methods of representation are more effective for people without a formal education in interpreting architectural drawings, but the models still rely on the observer having the ability to place themselves in that space in order to understand how their occupying the represented space would feel. This disconnect between our methods of representation and our clients' ability to visualize space can often lead to wasted effort based on a misunderstanding of the functionality of the space. Often misunderstandings such as these can cause the client to ask for redesigns, new methods of representation, or alternative design options which cost the architect and client both money and time. Often, these situations could be avoided if the client had a better understanding of the proposed space. Through the years, the architectural community has discussed the use of virtual reality technologies as a possible solution to bridge the communication gaps between designers and the people they design for.

Virtual reality allows the user to experience a space in an immersive visual way through the use of technologies that place a user in a digital representation of a space. Virtual reality has manifested itself in many different ways as its development has continued, from full room installations using projectors to lasers which project images directly onto a user's retina. Recently virtual reality has seen a resurgence with the release of the newest generation of commercially available head mounted displays. Although these new devices are designed primarily as display devices for the gaming industry the commercial availability and open source nature of many of these platforms allows them to be used by a variety of different fields including architecture. Virtual reality provides architects a new lens for interacting with and presenting their projects in the digital realm, which traditional two dimensional representations struggle to match. Now with the next generation of commercially available and affordable personal virtual reality devices right around the corner, how can architects best utilize these new tools to better showcase their work and facilitate communication between their visions and their clients? It is also necessary to begin to study how and when the tool is best utilized in the design process and when it is most effective as a presentation tool. Testing how realism affects understanding of architectural space allows us to test a small slice of the tool's stated uses and allows us to gain a better picture of where the tool fits in the architectural process.

Until recently, the benefits of having clients better understand the space they were being presented were there, but the technology itself was always too bulky, costly, and low resolution to justify incorporating it into any average firm's workflow. Throughout the years there have been many attempts to bring virtual reality into the realms of architecture but now, more than ever before, virtual reality has become affordable and legible enough for architects to begin to integrate it within their work-flows. The devices are now reduced from the massive room sized installations down to an easily portable head mounted display along with a pc or laptop with the appropriate software. With the reduction is size the technology also has become much more affordable for the average person, making them far more accessible to the architectural industry as a result. On the software front, things have also advanced to the point were the software that is being used to create these virtual environments now integrates with most three dimensional architectural models making it simpler than ever to transfer an existing architectural model into virtual reality. Visualizing virtual environments through these new technologies has the potential to create an unparalleled level of communication between designers and clients by giving architects the power to place their clients within the spaces they design. This can translate not only to a better understanding of space but also an improvement in the ability of the observer to articulate their critiques about the spaces. Perhaps even more powerful then simply understanding a space that is being presented to them, virtual reality also allows clients to get a better understanding of how the changes they propose affect the space and can facilitate a greater engagement with the design process. The purpose of this study is to test some of these principles and better understand how users understand and interact with virtual space using virtual reality in an architectural context.

Many studies have been carried out on the benefits of using virtual reality as a tool for conveying and documenting space in architecture

figure.1: Example of Oculus DK1 in use.

but how does the rendering quality of the spaces being represented affect the user's perception of that space, and how does it affect their retention of the knowledge gained through the experience of that space? This study is a preliminary user based experiment designed to determine how the level of rendered realism in a virtual environment affects the users' spatial memory. This allows us to evaluate their ability to understand the space not simply as a test of image-to-image recall but as a three dimensional immersive experience and the creation of cognitive spatial maps. This test focuses on how spatial memory is affected by the level of realism in the rendering of the virtual space the user inhabits. It is designed to test the hypothesis that a more realistic virtual space is a better tool for presenting to clients because they will have a greater understanding of the space as more detail is given to the model. Answering the question of how realism affects a user's perception of space in virtual reality will allow the test to draw conclusions about the stages in a project in which virtual reality becomes most useful as a design presentation tool and how to optimize the experience of virtual reality so that clients reap the most benefits from its incorporation into a project. The conclusions drawn from this study are designed to inform a larger and more in depth study on this topic at a later date and also to explore the validity of the initial hypothesis.

History of Virtual Reality

Virtual Reality, like many technologies, has it's roots in science fiction writing in the short story "Pygmalion's Spectacles" by Stanley G. Weinbaum in 1935, which described a goggle-based method for experiencing simulated environments that rather closely mirrors the current perspective on the technology but also incorporated things such as smell and touch to immerse the user. As a technology, virtual reality first made an appearance in the early 1960's with two notable visionaries in the field, Morton Heilig and Douglas Engelbart who were both working at roughly the

figure.2: Morton Heilig's Sensorama.

same time to develop very distinct versions of virtual reality. Heilig's focus was on virtual reality as entertainment. He developed a device which was called a Sensorama, a new method of viewing films which allowed the user to view a stereoscopic three-dimensional film in an immersive pod that would also provide haptic feedback, which is any sort of physical force feedback, to the user by tilting and manipulating the seat. Sensorama also had the ability to trigger smells at predetermined points within a film. Engelbart took a more technologically exploratory route and developed the first virtual reality display that was designed to be used in conjunction with a computer as a method for displaying information and interfacing with the computer. Neither of these technologies developed into wide use but both went on to shape future innovation in the field. In the mid to late 1960's a new form of virtual reality was introduced by Thomas Furness who developed a virtual reality flight simulator for the United States Air Force. It was designed to simulate a cockpit of a fighter jet for the user in order to better train air force pilots. Virtual reality and augmented reality, which is another form of virtual reality that projects virtual elements into real space instead of creating a purely digital environment, as we know it today was pioneered in the work of Ivan Sutherland and Bob Sproull who are credited with creating the first method of representing space in virtual reality through the use of a head mounted display device as well as developing a gesture based system of manipulating the environment in

figure.3: Ivan Sutherland's head mounted display.

the form of "The Sword of Domocles", which was a wand that allowed the user to interact with the space without having to visualize their own body. The inability to visualize the body while wearing a head mounted display makes using common input tools difficult for most users to manipulate. Motion and gesture based controllers solve this issue by allowing physical movement, which the user can perform without sight, to control the space. Sutherland and Sproull's virtual reality device was a more advanced version of the head mounted display, which allowed the user to visualize low detail wire-frame spaces and manipulate those spaces through the control wand. There were still significant drawbacks to the technology at this stage, the head mounted unit was extremely heavy

figure.4: Battletech virtual reality pods.

which forced the researchers to suspend the unit from the ceiling in order for it to be worn and the limited amount of data that could be represented kept it from being a useful tool outside of the lab. At this stage the technology was still far too new and unrefined to have any real impact outside of the virtual reality research sphere (Britanica).

Through the early years, virtual reality systems were mainly developed as simulation tools that are developed to aid in the learning of specific tasks such as in the case of Furness's flight simulators. The trend of virtual learning devices continued into the 1980's and saw the development of simulators in the medical field designed to aid surgeons in procedures as well as virtual interfaces that allowed users to remotely manipulate machines through the use of virtual reality technology. In the late 1980's and early 1990's virtual reality again started to make way into the public's attention when it began its return to the sphere of entertainment in the video gaming sphere. The earliest implementations of virtual reality in the field of video gaming were basic head mounted systems attached to arcade cabinets. They allowed the user to visualize the environment but they manipulated the game using standard video game control methods.

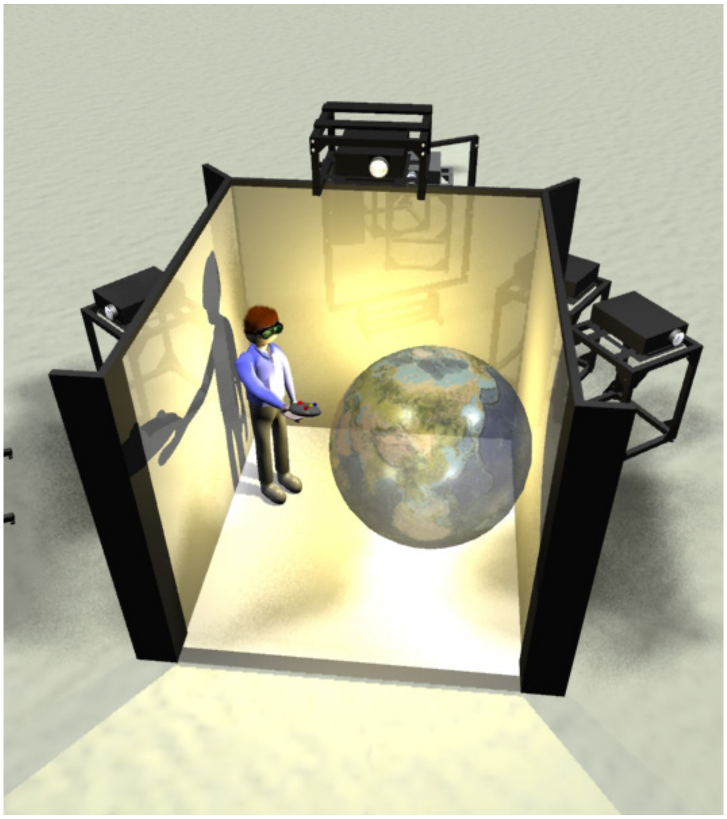
In 1990 the first Battletech opened in Chicago. The Battletech emporium was modeled after an earlier virtual reality simulation system known as SIMNET and was designed to operate as a multiplayer gaming environment in which users would be placed in individual pods. These would display an immersive virtual environment for the user to manipulate and participate in a multiuser virtual reality simulation. This would also be one of the first points in time that virtual reality would be widely available to be experienced by the public

(Britanica).

During this same period of advancement in virtual reality video games a new virtual reality platform was being realized through the Electronic Visualization Laboratory at the University of Illinois at Chicago which was known as CAVE. The CAVE system is a platform that utilizes a small space enclosed by rear projection screens which display the virtual environment, the user is then given 3-D glasses and is able to interact with the space through tracking software that is able to read the glasses position in the space. The CAVE platform has continued to advance to the present day and now incorporates many of the more modern advances made in virtual reality such as full three dimensional head tracking, high resolution imaging, and the ability to move and manipulate the environment. CAVE solutions for virtual reality have been widely used in a variety of different fields such as medical practice, landscape architecture, simulation design, data visualization, interface design, and architecture (Britanica). The main drawback of the CAVE system is the time and space requirements associated with the system. CAVE requires a static installation that is generally the size of a wall or small room. The setup requires several projectors as well a computer to run the simulations, (Febretti, 2014) and the installation often requires professionals to set up the equipment (Achten, 2004), making CAVE platforms less then ideal for use within the architectural field because their limitations in mobility and necessary affordances do not match the need for virtual reality.

The newest generation of virtual reality platforms, such as the Microsoft Hololens and the HTC Vive, has once again taken the form of head mounted displays but are now targeting home consumers as their main demographic. This renewed excitement for the prospect of virtual reality began with the crowd funded virtual reality display device called the Oculus Rift. Oculus first began their campaign in 2012 and, in conjunction with the crowd funding campaign, released their first developer kit which allowed the public to purchase and experience a prototype of the technology. After the success of the initial development kit Oculus released a second version

figure.5: CAVE VR display system



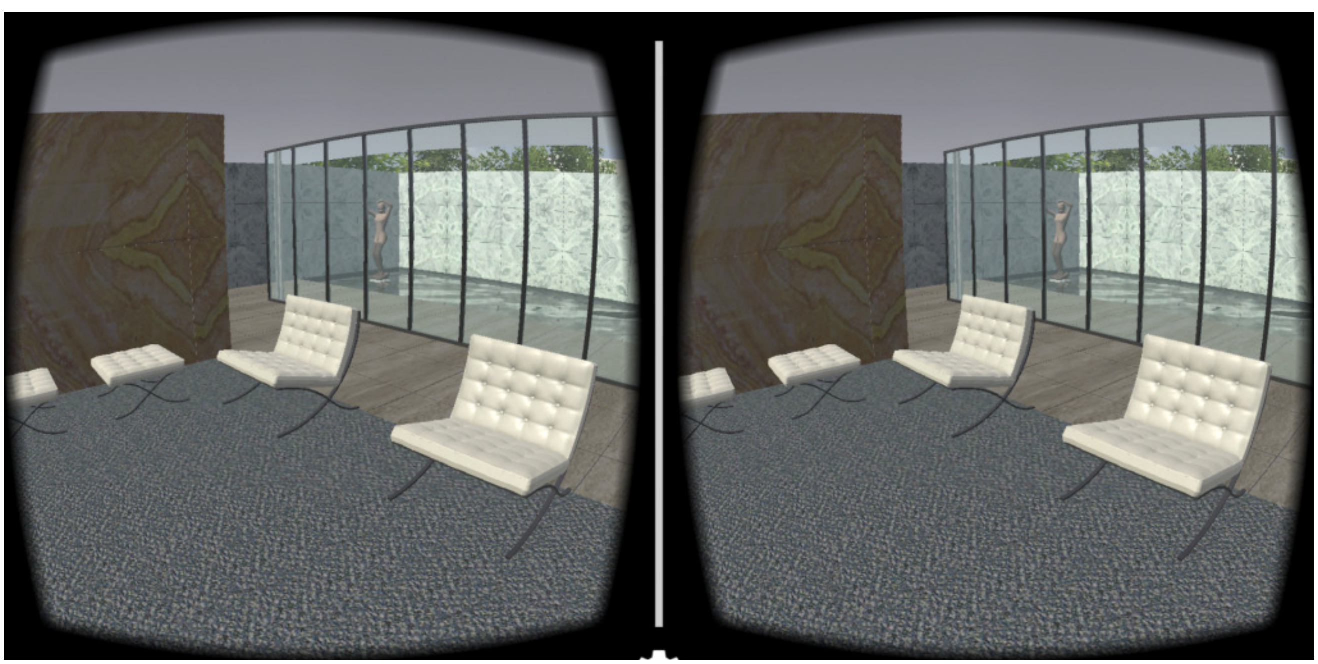
of the prototype which went on sale in 2014 (Avila, 2014). Both of these prototype head mounted displays have been popular among the gaming community and served as a jumping off point for the next generation of virtual reality and once again despite the platform being designed mostly with gaming in mind, other industries began to investigate the technology for uses in their own fields. With the success of the Oculus Rift several other electronics giants also began development of their own versions of the technology and currently there are commercial virtual reality head mounted displays in development by Sony, Microsoft, Google, and Valve. There has also been a boom in the field of lower cost virtual reality alternatives such as the Google Cardboard and the Samsung Gear VR, which offer low cost head mounted displays that allow the user to utilize any smart phone to view virtual environments (Bolas, 2013).

These new advancements in virtual reality have taken wide steps in moving the technology out of professional and industry spheres and into the hands of the public. The focus on virtual reality as a consumer good has also allowed for other industries including architecture to take advantage of the technology to advance their own fields.

VR in Related Fields

Virtual reality's documented ability to convey space and immerse the user in a world which may or may not represent reality has made it an invaluable tool in many differing fields where the ability to convey space is an important element. Currently the largest and most publicized use of the newest generation of virtual reality devices is as a display and control device in the video gaming

figure.6: Barcelona Pavillion represented in VR



sector. It's popularity within this sector is attributed mostly to its ability to immerse the user in a space, creating a much closer connection between the user and the gaming environment then they would have experienced simply interacting with that space through the traditional monitor set-up (He, 2014). This is mostly attributed to the wide field of view which allows the content of the experience to encompass the player's entire vision. The experience of virtual reality in gaming also better allows for users to gauge their own relationship to objects within a simulated space, which allows them to better perceive essential space defining elements such as depth (Ardouin, 2014). Being able to accurately recognize spatial characteristics of a scene is useful for creating an immersive environment connects the players to the events happening around them. The other important thing that virtual reality gives to the field is a variety of new methods of interfacing and interacting with a virtual environment, such as the use of head tracking to manipulate camera controls or virtual body position in space (Spiller, 2000). A variety of new methods of control and interface designs that are required to be intuitive and accurate make games an ideal place to find new methods of interacting with virtual space. The gaming community has also given the larger virtual reality community several methods in which a multi-user virtual reality environment may be configured. These environments could be translated from gaming into a method of presenting architecture to large groups of clients (Freund,), which is especially important given the trend of personal virtual reality (Thomas,).

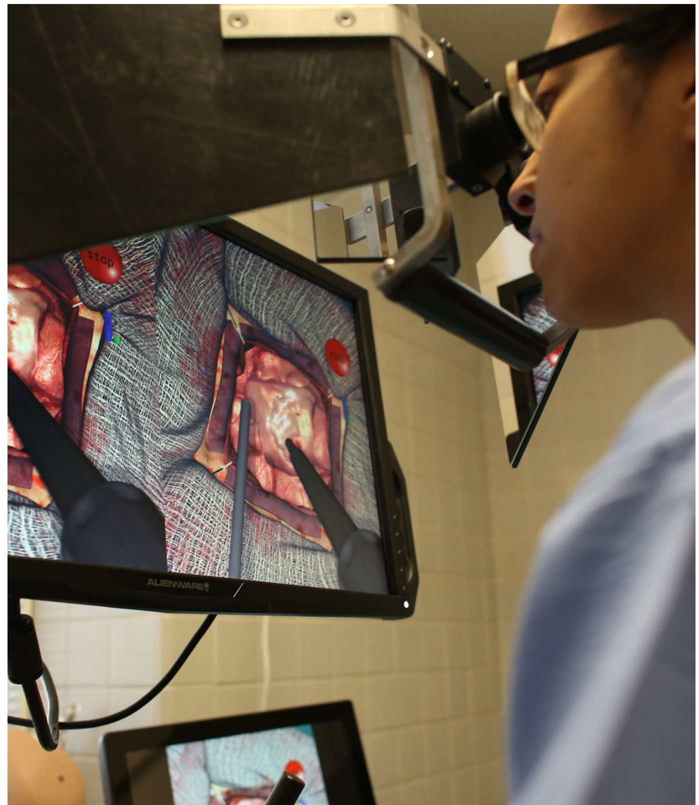


figure.7: Surgery simulation using virtual reality.

Since virtual reality's inception medicine has been one of the larger fields to make use of it's potential. Simulation of medical procedures began in virtual reality fairly quickly and were effective to teach complex medical procedures to students and practicing medical professionals. The use of virtual reality in the medical field allowed practice on procedures without the need for costly model humans or cadavers, which are often in limited supply. This also allows doctors and students to practice as often as they have access to the virtual reality simulators. In order to be an effective simulation in the medical field it must be accurately represented and have controls which are reflective of the task which they are completing. The medical field is where most studies and documentation on the positive effects of having inexperienced people utilize virtual reality to help them learn have occurred. There is a distinct positive correlation between those who use virtual reality and those who do not in terms of preparedness for real life equivalent tasks, which indicates that virtual reality is a positive teaching tool (Waller, 1998). The medical field has also begun using virtual reality to remotely control machines operating on patients, which indicates the level of spatial awareness one possesses within a virtual environment (Gallagher, 2005). Should these principles be carried from medicine to architecture, many of the benefits that the medical community have documented could be utilized in service of designers to help their clients understand their projects.

Virtual reality also has begun to have an impact in historic preservation and landscape architecture. Documenting historic buildings through digital models is nothing new (Kalarat, 2014), so it stands to reason that if digital models exist translating those three dimensional models into virtual environments may be a positive step in allowing a new generation of users to experience the buildings of the past. (Komianos, 2014) While there have been relatively few attempts to recreate historical or architecturally relevant buildings for public consumption via virtual reality, there have been attempts to move in that direction by several historical preservationists (Komianos, 2014). Recreating these significant buildings allow them to be studied and experienced spatially from anywhere in the world, even years after they have been demolished (Webel, 2013). A few architectural preservationists have used this method to recreate buildings in the past and during the early years of virtual reality the difficulty of creating virtual environments made the translation process too difficult to make the process viable. Without the computing power to create a realistically rendered environment the translations of the buildings into virtual space was not effective as effective to illustrate and capture the character of the space accurately (Xia, 2008). However as rendering methods and qualities improve and the process of moving architectural models into virtual reality becomes simpler the uses for historical preservation will be far greater (Sheng, 2013). There have also been several journal articles written on the positive effects of virtual reality in the field of landscape architecture which can translate into architectural applications. Immersion into a virtual space allows users to experience that space from the point of view of the occupant, allowing design characteristics such as scale, materials, and texture to be experienced. This makes the learning process a much more streamlined and easily explained system because the user does not have to interpret space through two dimensional methods of representation (Yuan, 2012). Aside from the quicker understanding of the space, virtual reality also allows for users to clearly see the impact of their design decisions on the project as an experience. This is especially true when the simulation of space gives the designer immediate feedback by allowing the designer to manipulate the space while inside the simulation. Since the process is an immersive one, changing elements can be experienced as an occupant would experience them and allows the designer to more clearly articulate potential benefits or detriments any given design decision could have to the integrity of the design as a whole.

VR in Architecture

Architecture's relationship with virtual reality has been fairly limited up until this point with almost no practicing architects incorporating virtual reality into their work-flows as a routinely used method of presenting design work to clients despite documented evidence that it has substantial benefits. Virtual Reality as an architecture tool has mostly limited itself to academic spaces where technology is more accessible and projects allow more freedom to experiment with technology that has yet to prove itself in a professional setting. With the new technological innovations that make it easier then ever to incorporate, and the rise in affordable virtual reality solutions to architects now could be the time when virtual reality begins to make an impact on the practice of architecture (Maleshkov, 2013).

figure.8: CAVE virtual reality being used to view an architectural space

Aside from virtual reality's uses as a representation tool for client based presentations it has also been shown to be invaluable to designers through studies that show how incorporating virtual reality through different stages of design function for the architect. The use of virtual reality has been shown to have increasingly beneficial responses by designers as the project progresses through the design process. Most designers find the virtual reality platform unhelpful in the initial site work and diagramming stages of the architectural processes but once the project moves to massing there is a spike of positive response by designers. After massing all subsequent steps show a steady increase to the number of positive responses to the technology (Abdelhameed, 2014). With the increased understanding of the space through the first-hand experience of the project the designer is better able to understand how changes shift the environment and the designer is better able to make judgements about whether a given change is functioning in an advantageous way for the overall design (Tahrani, 2007). Experiencing a project spatially rather than abstractly also allows for the designer to better understand the physical experience of the building, which allows for them to make more accurate assessments of the comfort level of the space, by judging things such as lighting or spatial characteristics, before presenting their designs to clients (Al-Attili, 2009).

The befits of virtual reality as a presentation tool have been documented in studies such as in “Evaluating the use of Virtual Reality as a tool for briefing clients in architecture” which utilized clients in a study to see how they responded to questions based on an exhibited virtual model of their project. The study took clients through an immersive representation of the space using a CAVE-like virtual reality environment and then asked them a series of questions based on their experience of the space through virtual reality. The virtual reality space was presented as an immersive animated walkthrough which did not give the clients free movement through the space. The overall conclusion to the study was that the clients were able to better understand the project when the space was presented through this lens. They showed a better understanding of tangible aspects of the space, such as distance between themselves and objects or heights of ceilings in the space. Compared to the previous two-dimensional methods of representation, they were better able to recall spatial characteristics of the model like size of rooms in relationship to other rooms in the model, where things were located within the environment, and sequence of rooms through the space. Experiencing the space also led to a greater sense of immersion into the environment and the clients were better able to picture how they could potentially influence the space and what differences those changes would have on the space (Patel, 2002).

Another architectural study designed to investigate the benefits of using virtual reality in an architectural context was conducted at the Royal Danish Academy of Fine Arts and was titled “New Virtual Reality for Architectural Investigations”. This study used the first Oculus rift development kit to allow users to move through an immersive low detail space and then asked them a series of question to determine how the Oculus affected their understanding of the space. The conclusions were very similar to the previously discussed study and showed that experiencing space as a virtual environment has an overall positive effect on their ability to accurately gauge the environment that they are placed in. Participants were able to remember and recall distances and scale related questions quickly and consistently. The study also allowed the users to view the simulation with textures and without textures and showed that most users preferred the textured model to the blank model because they found it more immersive

figure.9: Oculus Rift (commercial release)

and relatable. Some of the problems of the early hardware are also illustrated throughout the study. The participants often found navigating the space using a traditional video game controller difficult if they had no previous video gaming experience but once given instruction they were able to move through the space effectively enough to complete the study. They later greatly simplified the control scheme and found that by simplifying the control to a simple forward movement that there was a huge improvement in the participant's performance in the space. The low quality of the model coupled with the lower resolution, lack of head tracking, and framerate of the older hardware also saw a number of the participants experience simulator sickness, which is a feeling of nausea that is caused by prolonged exposure to virtual space, during the test.

Another study that illustrates the power of virtual reality as a presentation tool in an architectural context is "Spatial Cognition in Virtual Reality: Developing an Evaluation Technique for Representational Methods of Virtual Models". This study directly compared how different mediums of representation affected participant's ability to physically recreate a spatial arrangement of objects. In this test participants viewed an arrangement of walls in two dimensions on a computer screen, in a virtual environment that they could navigate with a controller, a virtual environment that they could control through physical movement, and a control group who viewed the physical real life arrangement. The participants were then asked to physically recreate their experience by moving the walls into a position that matched their experience. The conclusions of the study show that, outside of the control group, the participants who performed best at the task were those who viewed the task as a virtual environment. Out of the two virtual environments the participants who controlled the simulation through physical movement performed better which also seems to indicate an advantage to a more realistic simulation being a better method of conveying space to a user (Adams, 2013).

The architectural community has seen potential in virtual reality since it was first utilized to represent space but each previous generation of virtual reality platforms have failed to deliver a compelling enough product for it to be widely accepted as a tool for architects. Excitement for virtual reality has ebbed and flowed through the years with each new breakthrough in the technology promising to revolutionize but ultimately architects have found the technology's flaws outweigh their potential benefits. Creating architectural models in virtual reality has previously been seen as too difficult and costly to implement with previous generations of virtual reality (Boukerche, 2009). The high cost associated with the both the software needed to build virtual environments and the computing power needed to run the platform, plus any external necessary equipment needed to run the immersive environment, made the prospect of incorporation immediately unfeasible for architects. The software required to build virtual architectural models was extremely resource intensive and would not integrate well with existing architectural modeling software, meaning that any virtual model would have to be built from scratch. This required architects to double their modeling time and train themselves in an entirely new software suite to create a virtual environment. The biggest issue in previous versions of virtual reality hardware was always the portability of the technology as well as the associated high cost. Virtual reality, before the modern emphasis on personal head mounted displays, had generally focused on CAVE-like virtual environments that required a static space dedicated to virtual mock-ups with little to no portability (Schulze, 2014). This created a dynamic where the only reliable method of presenting on these platforms would be to require the client to come to a location that had a CAVE set-up, whether that was a set up in an office or a third party location such as a nearby university that would allow their space to be rented. This created a situation where virtual reality was not something you could bring to any presentation and therefore disinsentivised its use.

The new generation of virtual reality systems seeks to remedy many of the old problems that hindered virtual reality's acceptance in the architectural community as a tool for representation. The most obvious advancement in the technology is the quality of the simulated environment which is supported by the hardware (Sato-Wang, 2006). All new virtual reality platforms being released today support high resolution displays, most of which are now 1080p or higher, with high refresh rates of at least 60HZ meaning that they can provide a seamless virtual environment and have the ability to display that environment at a high enough framerate to be displayed at a comfortable level for human interaction, which is generally 60 frames per second minimally and 75 frames ideally (Billger, 2002). Most hardware also has head-tracking abilities and gyroscopic tracking which when coupled with the support for high resolutions and high frame-rates does a lot to reduce the effects of simulator sickness on users. The new focus on virtual reality as a consumer product has also significantly reduced the cost of the hardware. Head-mounted-display devices with simple USB interfaces serve to make them far more flexible for transporting to anywhere they are needed for a presentation. The simplification of interface also means that these new virtual reality platforms have the flexibility to be used with any computer as long as it is powerful enough to present a virtual environment and has the appropriate software installed for the device, which means that the architect may not even be required to provide the computer if one is available that meets the requirements (Araújo, 2012). Probably the largest advancement in the field of virtual reality for architects is the wide availability of software which supports creation of virtual environments (Su, 2012). Two of the most popular gaming engines used to build virtual environments are now free to use for anyone wanting to experiment. This gives architects access to a new toolset that previously required a large capital investment to implement. These engines are also far more integrated into programs that architects already use to build and render models, making it a much quicker process to incorporate virtual reality on top of their 3-D modeling and rendering process (Angulo, 2014). This process still requires training in those engines in order to incorporate virtual reality but the process is now far simpler and no longer requires that models be rebuilt for engines that do not support architecture models.

Issues remaining in Virtual Reality

The biggest issue still present in virtual reality that has not yet been resolved is the issues around simulation sickness (Cobb, 1999). Simulation sickness is broadly defined as the feeling of nausea that people sometimes experience when placed into virtual reality simulations. It is more likely to occur with models that are less than ideal for human perception. It has been present in the technology since the first virtual reality flight simulations. There are several distinct theories on why users in virtual space experience simulator sickness. The most prevalent theory is that when the motion of the user doesn't translate to an appropriate movement in the simulation the user's brain processes that as if it is a symptom of poisoning and will respond by causing nausea in the user in an attempt to combat the poisoning affecting the user's vision, this is known as sensory conflict theory. This can be caused by the user not feeling like their real life motions are translating appropriately to the simulation as well as the software itself not being designed appropriately to virtual reality standards for comfort, which have been broadly outlined by the virtual reality community. When the brain's expectations do not match the experience of the simulation it causes dizziness and eventually sickness in the user. Software issues such as low frame rate within the simulations, removing camera control from the user quickly, or quick unexpected transitions between scenes can all bring about this feeling of nausea that is explained through sensory conflict theory.

The second theory is based on the idea of postural stability, very similar to sea sickness, and is said to be caused by our body's need to constantly make small adjustments using accurate sensory input. When accurate sensory input is not available it causes the body to feel as if it needs to compensate for this discrepancy and results in nausea. This theory defines simulator sickness as a temporary problem mostly caused by the user's lack of experience with the feeling of being in a simulated environment and that the most effective method of treatment is long-term exposure to virtual reality simulations. This theory states that the more time a user is exposed to the effects of virtual reality the less likely they are to feel the effects of simulator sickness (Lewis-Evans, 2014).

Both the sensory conflict theory and the postural stability theory come together into a complete picture of why users experience simulator sickness in virtual environments. Studies conducted on development of best practices in virtual environment design have shown that these theories work in conjunction to provide a clear picture of the causes and possible solutions to the issues of simulator sickness (Kolasinski, 1995). The sensory conflict theory is supported by the fact that user's experiencing simulated tasks that they are more familiar with in reality are more likely to experience simulator sickness then those inexperienced with the task. The postural instability theory is supported mainly by the order in which symptoms generally occur, people reporting balance problems and dizziness before becoming nauseous. It also is a better indicator as to why users experience less simulator sickness as their exposure to virtual environments increase. While these theories provide a strong narrative for describing the causes of simulator sickness they all have a low predictive value and are thus difficult to measure accurately for study.

Technological advances since the initial stages of virtual reality development have significantly reduced the prevalence of simulation sickness in the experience of virtual reality but it has not completely erased it yet. The addition of head tracking to head mounted displays was one of the biggest advances in combating simulator sickness because it allowed users to move their head naturally and have that correlate to movements within the simulation, therefore reducing the disconnect people feel between their physical inputs and the resulting movements in virtual reality which causes simulation sickness. Most of the effects of simulator sickness can be reduced through the design of the simulation itself by abiding by a few best practices that have shown to provide the use with a much more stable environment. A few of these methods are to continuously provide high frame rates, do not use excessive flashing lights, use accurate camera heights, limited changes to speed of movement through a simulation, and limiting field of view (Ben Lewis-Evans, 2014).

Aside from the general issues still present in virtual reality, issues still remain with virtual reality as a tool for architectural representation specifically. The biggest and most obvious issue with presenting virtual reality to clients is that the technology still only supports a single user at a time. The user's experience can easily be projected to others outside of the simulation but without control of the experience this is the equivalent of watching an animation or other two-dimensional means of representation and would lack the benefits gained from using virtual reality. There are methods and means for designers to create a multi-user virtual reality environment but it would require the presenter to multiply the required hardware units by the number of participants which would reduce both the cost effectiveness and the portability of a virtual reality presentation significantly. While designing a virtual environment for a single user may be simple there is still no easy way to design a multi-user environment making the use of virtual reality to multiple clients difficult even outside of the hardware limitations (Thomas, 2014). The only real solution to this is to simply use a single unit and allow clients to take turns in the simulation, which is not ideal from a time or pacing point of view.

Visual and Spatial Memory

The measure that is being used in this test to gauge whether or not participants are gaining

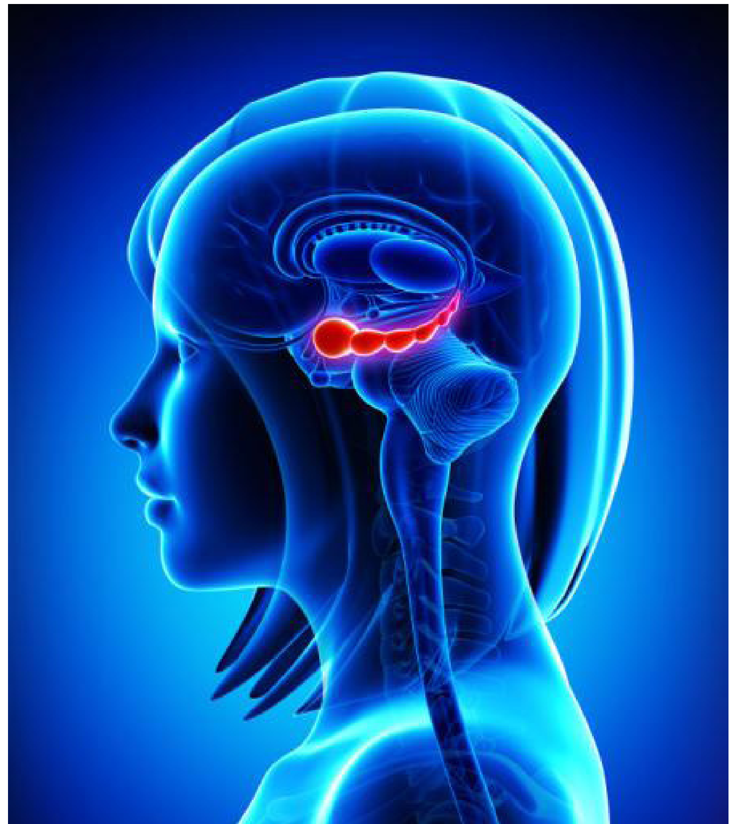


figure.10: Hippocampal region of the brain.

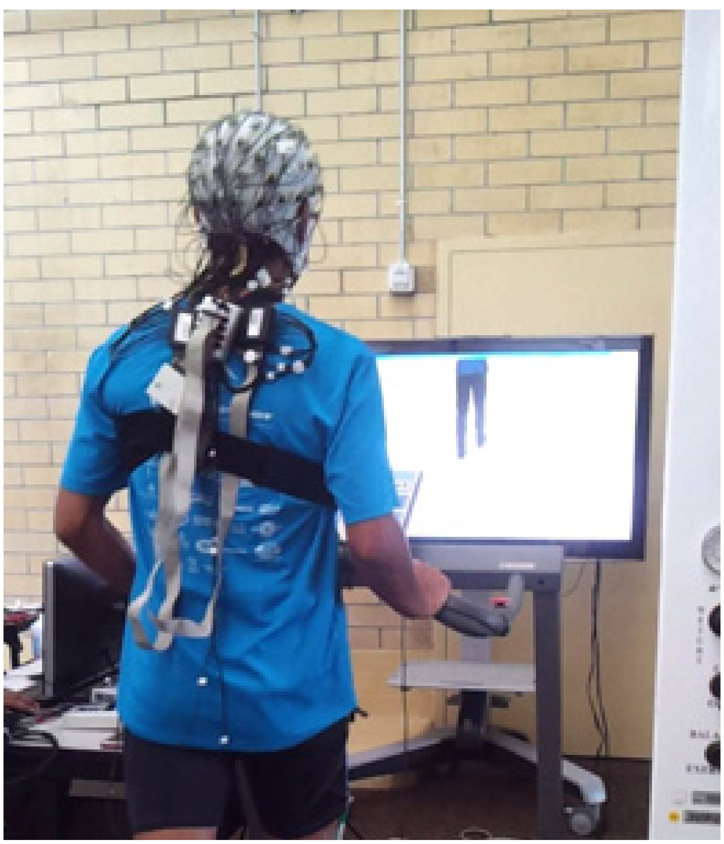
a better understanding of space as the detail levels change, is the occupant's spatial memory. Spatial memory is defined as the part of memory that is responsible for storing information about one's directional orientation and information about the surrounding environment (Shelton, 2004). Cognitive psychology explains this as the part of memory that allows a person to navigate through space by defining relationships between objects in a scene (Burgess, 2003). Spatial memory is the tool the human brain uses to create a model of a space or environment in order to better navigate that space (Schumann-Hengsteler, 2004). The hippocampus is the main section of the brain required for development of spatial memory which is also the part of the brain in charge of forming memories about experiences and events in one's life (Morris, 2004). Visual memory, on the other hand, is simply the brain's ability to recall visual information processed through the eyes. The two often work in conjunction to create a clearer picture of an environment, but visual memory is explicit recall of specific visual patterns to create a metal image (Chun, 1998).

Spatial memory is often studied through the use of mazes. Sending test animals through mazes repeatedly gives the animals a clearer picture of how to complete a maze in the most efficient manner possible. Repetition of an event allows the brain to form a cognitive map of the environment and allows the occupant to better understand how to navigate that space, which is how the rats are able to form an optimum path through the maze with repeated attempts. This is spatial memory in action and it is often tied closely to learning (Creem-Regehr, 2004). Evidence for this has been studied by neuroscientists in patients who have epilepsy that has damaged the hippocampus in the brain. Patients who suffer this kind of brain damage often have difficulty in finding or remembering locations of objects in space. They also have difficulty forming a clear picture of how a space comes together and how to best navigate through a space. It has been noted as a one of the symptoms of Alzheimer's disease which also attacks the hippocampal formation in the brain, and manifests itself in a disoriented state where the affected person loses track of where they are. Spatial memory is also strongly tied to object memory (Postma, 2004). Object memory is what allows the brain to comprehend an object as a three dimensional form with material and texture which is a component of that form (McNamara, 2004). Spatial memory uses these same principles to form accurate cognitive maps of the person's surrounding environment. The human brain often creates these mental maps of environments through the use of landmarks and using those landmarks to determine things like adjacencies and relative scale, which allows for the brain to create a more accurate picture of the environment being interacted with (Allen, 2004). This study measures spatial memory as opposed to visual memory because it is a better gauge for how well a space is understood as a three dimensional form rather then a series of recalled images.

VR and Cognitive Psychology

Virtual reality's effects on the human brain are well documented and create a clear picture about how virtual reality can affect the cognitive processes of those who experience it. Exposing someone to a virtual environment can have a significant impact on their cognitive processes, things from pain response to how users perceive time have all been studied in virtual space. It has been shown that the more immersive the environment the more people accept the simulation and treat the simulation as if it were real in a much more impactful way than two dimensional video or imagery does (Ponto, 2014). Virtual reality has been used by psychologists and medical professionals to treat patients suffering from a wide variety of psychological disorders through a process known as virtual reality therapy (Rizzo, 1997). These practices have been shown to have positive impact on patients suffering from conditions like post-traumatic stress disorder and even certain types of phobias (Shelton, 2004). Virtual reality therapy is based on the idea that repeated exposure to a specific experience will recondition the brain to respond differently to stimuli which may have in the past provoked a strong negative reaction from the patient. Since virtual reality is treated like a real life experience, rather than an image or a story like you would get from a film, the user is able to create positive associative experiences in a safe controlled virtual environment. It has also been very effective in the treatment of people who suffer from neurological disorders which affect or damage parts of the brain that deal with memory (Optale, 2010).

figure.11: Testing a subject in VR



One of the largest fields in which virtual reality has proven to be an effective tool is in the area of teaching and developing memory. Through immersion in an environment the body's cognitive processes adapt to more closely align with the virtual environment in which they are present (Parsons, 2008). The prevalence of virtual reality in simulation design, which is the development of simulation which mimic real world tasks or environments, speaks to its ability to convey information and facilitate learning through the completion of tasks within virtual reality. The close ties that virtual reality has to memory make it an ideal teaching tool because as the immersion in a task is increased there is also a positive correlation on recall (Dinh, 1999). With virtual reality being the most immersive platform, outside of actually performing the task itself, it has become an invaluable teaching tool.

VR and Spatial Memory

Virtual reality and spatial memory have a unique and intertwined relationship that has been well documented as one of the key advantages that the technology has over other existing methods of representation in fields such as architecture. The use of virtual reality activates the portions of the brain that are associated with the formation of memory through experience, this also happens to be the portion of the brain most closely associated with spatial memory. Many of the tasks designed for lab animals during the initial stages of testing and creating evidence for spatial memory as a neurological function have since been adapted for testing on humans using virtual reality (Parslow, 2004). These subjects were monitored during these virtual reality studies using functional magnetic resonance imaging (fMRI) in order to determine the active areas of the brain while navigating through large scale virtual environments (Montello, 2004). The conclusions of these studies showed an emphasis on activity in the hippocampal region of the brain which confirmed that, as navigating through physical space, navigating through immersive virtual space creates a very similar set of brain activity. The transfer of this testing into virtual environments showed comparable results to the physical studies that were preformed on rats (Gillner,1998). This has led to virtual reality becoming an academically recognized standard for use in tests relating to areas of psychology dealing with spatial memory or object memory (Oman, 2000). Virtual reality has also been shown to decrease in effectiveness as the user gets older and begins to suffer deterioration due to the natural aging process (Moffat, 2001). These effects on the brain also correlate with a cognitive theory in psychology known as presence. Presence is a term which is used to indicate the level of acceptance that a person has of the situation they are currently placed in. Presence in virtual reality is often cultivated by stimulating multiple senses during a simulation to increase the immersion level of a virtual environment, this increase in immersion leads to occupants feeling a greater sense of presence in the simulation. An increased level of presence has been show to also cultivate a better response in brain wave functions relating to spatial memory (Lin, 2002). This activity within the brain provides a unique advantage for the architectural profession because it allows architects to experience space and form a better understanding of how that space functions as a physical environment because the brain is literally tricked into perceiving the space as a physical environment (Dünser, 2006).

Further evidence for the utilization of virtual reality having a strong impact on the spatial memory of the user comes by way of virtual reality’s use in monitoring and testing for damage or diminished spatial awareness in cases of damage to the hippocampal region of the brain. Virtual reality is now a common tool for assessing a patient’s abilities to navigate and explore space once brain damage has occurred in the areas of the brain affecting spatial memory. This allows for medical professionals to gauge the loss of spatial function by monitoring progress and performance in virtual environments while monitoring brain function (Wenigera, 2011). This method of testing has already been used on stroke patients with damage to the hippocampal region as well as patients suffering from clinical depression who also have shown signs of inhibited brain functionality in that area (Gould, 2007). As discussed previously, the medical field often uses virtual reality in therapies attempting to cultivate the creation of new memories in patients with this sort of damage to their nervous system (Brooks, 2004). Immersive models of virtual reality has been determined to be highly effective at building patient's sense of orientation and the formation of mental maps which allow them to begin to translate these abilities back to their physical interaction with their environment.

Virtual reality's use in simulation design and teaching also has its roots in its neurological effect on spatial memory. Since spatial memory is so closely tied to how humans create memories of events, it is also shown to have great benefits on learning (Schlickum, 2009). Teaching in virtual reality has been shown to have a comparable effect on the brain as it would if the skill being practiced in real life. As long as the level of immersion in the task is strong enough the effects of training in virtual environments have been shown to enhance the learning experience for those involved. This is also one of the areas in which the brain can become disoriented during the use of virtual reality. When an expert in a task moves into an immersive virtual reality simulation of that same task they have been shown to exhibit an increased susceptibility to the effects of simulator sickness (Gallagher, 1998). This effect is mainly due to the brain processing the slight differences between the physical world and the virtual world while perceiving both as real events. This leads to small changes being perceived as a cognitive failure and will manifest itself in the body as sickness or disorientation. This effect exhibits how the brain perceives virtual reality as a physical experience that is not separate from the real world and forms memories of that experience accordingly.

The Question of Realism

With the rising popularity of virtual reality and the new technologies in the field addressing many of the old issues that prevented its earlier adoption, the integration of virtual reality into the architectural field seems possible. However, in order for virtual reality to find its place in the profession there needs to be more research done to discover how to best utilize it and when it is most useful to those engaged with it. Moving the study from the general view of virtual reality to a small manageable subsection of virtual reality was in part inspired by the question raised in the study discussed earlier in this paper "New Virtual Reality for Architectural Investigations". This study used an earlier version of the Oculus Rift to show users a low detail sketchup model and they were asked questions regarding their ability to assess tangible qualities of the space such as distances and heights. The study came to the conclusion that interacting with that virtual space aided their understanding of the space. Subjects during the test had the ability to view the space both untextured or textured, but did not make any claims regarding this change to the space other than stating that it made the users feel more comfortable. There was also a consistent trend among studies in VR to rely on lower quality and lower detail models to conduct testing. The popular view of virtual reality is that it should transport you to a virtual world and from most experiences I have had with building in the technology, people want virtual reality to represent reality at the highest possible level. The technology has already been shown to have benefits to the architectural industry as a tool for designers and clients but the question of realism addresses at what stages in the process the tool becomes the most useful.

A building during a design process is constantly in a state of flux. There are many cases over the course of a design process where less detail and definition to the developing space can be seen as advantageous for designers to utilize. Architectural presentations utilizing blank physical models or linework drawings with no indication for material are common tools used by architects to clarify the field of discussion of a design. Virtual reality has been shown to work best as a tool to understand space but when presenting or working in less developed environments do we still receive the same level of benefits to our understanding, or is it simply the process of being placed in an immersive environment that provides the user with those benefits? The popular desire for fully realistic virtual environments discounts some of the utility

figure.12: Photo of testing setup


figure.13: Low-realism virtual space

that the tool could potential have at early stages in the design process or as a more diagrammatic tool. The following study has been developed to observe how spatial understanding is impacted by the rendering quality of the virtual environment. Through the conclusions of this study it is our hope that it will provide insights into how and when the tool becomes most useful to architects.

Outline of Study

Phase 1

The study begins with the subjects being seated in a rotating office chair at a station set-up. The chair was chosen in this instance because it is able to facilitate full rotation of the body. This allows the user to look any direction once placed in the virtual space. Being in a seated position also allows us to mitigate the possibility of some of the documented negative effects of prolonged exposure to virtual reality environments, such as simulation sickness. The chair will be positioned equidistant from the surrounding walls in the space so as to not allow the chair's placement in the space to favor a specific orientation. This is designed to facilitate the participant's visual interaction with the space by allowing him to decide how to orient themselves within the simulation without priority or restriction given to an arbitrary orientation outside of the simulation.

Aside from the configuration of the user in the space, the station was put together in a

figure.14: Medium-realism virtual space

desk space in the design machine group studio in Architecture Hall at the University of Washington. The Oculus station for the study is composed of a desktop computer, which will run the simulations using a packaged program from Unreal Engine 4, this allows the simulation to be presented to the user separate from the editing environment and allows the simulation to take advantage of the full processing power of the computer that may have been adversely affected by simultaneously running both the editor and simulation. These packaged projects are presented through the Oculus using a console command. The Oculus Rift head mounted display itself is attached to the desktop computer which is then placed in close proximity to the chair where the subject is seated so as to allow the user full range of head movement while taking into consideration the limitations of the length of cord provided for the Oculus Rift. A monitor connected to the desktop PC is also necessary to visualize the packaged project and launch the simulation in stereo mode through the Oculus Rift. The monitor also allows the interaction the participant has with the virtual environment to be observed through a duplicated visual environment from the Oculus onto the main monitor. This configuration allows the researcher to see what the participant is looking at during their time in the simulation and also monitor for potential bugs that occasionally have occurred over the course of the study. If the user had been observed doing something other then the task they are instructed to perform, they would have then be issued instructions to return to the task and if the program malfunctions the researcher had the ability to then remove them from the environment, relaunch the program and begin again. The final component is the Oculus Rift positional head tracking camera. This camera allows the user to move their head in three dimensions within space to give the participant a greater feeling of being immersed within the environment. This camera is being used in this study exclusively as a means to provide the simulation with positional data from the head mounted display and has no ability to record or document the participant during this study.

Once seated and before placing them in a virtual environment the participant was issued a series of instructions and an explanation of how the study is being conducted and exactly what is being tested for. Instructions for interacting with the space have been intentionally kept vague in order to allow the user the freedom to observe the space as they would if they had been placed in a real environment. Since no movement controls are provided the instructions for interacting with the space can be limited to “move your head to look around the space as you would naturally”. Since the Oculus Rift has both positional and gyroscopic head tracking, this should be the only instructions that are necessary to give them the full range of interactions intended for this study. The participants were also instructed that since the still images they will be identifying once removed from the simulation are created in a separate rendering engine that they would notice changes to lighting, color, and texture between the simulation and the images. They were then instructed that the only changes they will be asked to observe are changes

figure.15: High-realism virtual space

to the geometry of or objects within the space they inhabit.

The explanation given prior to the beginning of the test is detailed and specific because we wanted to prevent the subject's intuitive learning swaying the results to the study. This was an issue on whatever the randomly chosen first environment happened to be. By giving a detailed explanation they were more prepared to answer questions on the initial simulation. The participants were also told that they were going to be placed within three separate simulated virtual environments using the Oculus Rift at different levels of realism. They are told that they are going to be given a minute and a half to observe and memorize the space after which they were removed from the simulation and asked to respond positively or negatively to a series of images that will either reflect the space or have something about them altered. The participants were told that they had the choice to talk through the images if it helped them come to a decision on the image but no information would be recorded aside from the final positive or negative answer. A positive answer is give to any images that the participant feels accurately represents the space that was experienced and a negative response is indicated for any images that have been altered from the simulation. The question images were taken from various angles within the space and reflect the same level of realism as the simulation the participant had just experienced. This detailed explanation was chosen because it guides the subject's interaction with the space without giving them specific instructions as to how to interact with the space allowing them to interact with the intention to remember their experience. A detailed method of explaining the study is also needed because without clarity in the explanation, the participant may misunderstand the first stage of the study and perform poorly because of a lack of understanding of the task, and perform better on the subsequent tasks because they have learned how to better approach the problem.

Phase 2:

Phase two of the study places the participant in a series of three separate virtual environments that represent a different level of realism. The first level model is the lowest level of realism and contains flat uniform lighting with no shadows and all geometry within the model is represented using blank materials. The second level model retains the lack of materials but adds realistic lighting to the scene. The third level adds realistic materials to the scene and attempts to look as realistic as possible. The models contain the same geometric data in order to make the models as similar as possible to one another so the only thing being compared is the level of rendering detail present in the scene. Adding and removing physical detail from the project would have altered the space significantly between levels and would have brought more unconsidered variables into the simulation which may or may not have swayed the results in some way.

Once the explanation is complete the subjects are ready to begin the actual study. The first step is to give them the Oculus Rift head mounted display and allow them to put the device on their head, they will then be told to adjust the head set so that it is comfortable on their head. The display will remain in a sleep state until the subject is comfortable and ready to continue. During this set-up and staging period the realism level of the simulation will be randomly chosen from the pool of three levels of realism and once the participant has indicated they are ready to proceed the chosen environment will be launched. Once launched the experimenter then tells the participant that once the environment is set to stereo mode for display in the Oculus they will receive a health warning, which is a default warning displayed by the Oculus Rift before a simulation. Once the health warning leaves the display the timer will begin and they can begin to interact with the environment.

Once inside the simulation the participant will been timed for one minute and a half, during which they were given no additional instructions. Inside the virtual environment the user has the ability to move their head both rotationally and three dimensionally in space to observe the environment they have been placed in. The participants were also to remain stationary within the space and be given no method of instigating or controlling transformational movements within the simulated space. It was decided that no simulated walking controls would be provided

	A	B	C	D	E	F	G	H
1	SUBJECT:	KEY	T1	T2	T3	T4	T5	
2	DATA							
3	ARCHITECT	X	Y	Y	Y	N	N	
4	DATE	X	1-Jan	20-Jan	20-Jan	20-Jan	22-Jan	
5	TIME	X	0:00	3:30PM	4:00PM	8:00PM	7:30PM	
6								
7	LEVEL 1 IMAGE ANSWERS: (order:y/n/:X/O)							
8	SIM ORDER:	X	1	3	2	3	1	
9	0	N	6:Y:X	7:N:O	9:N:O	9:N:O	7:N:O	
10	1	Y	3:Y:O	9:Y:O	5:Y:O	7:Y:O	5:N:X	
11	2	N	7:N:O	2:Y:X	1:N:O	6:N:O	8:N:O	
12	3	Y	5:Y:O	4:Y:O	8:Y:O	5:Y:O	3:Y:O	
13	4	N	10:N:O	8:N:O	2:Y:X	3:N:O	9:N:O	
14	5	Y	4:Y:O	10:Y:O	7:Y:O	1:Y:O	2:N:X	
15	6	N	1:N:O	6:N:O	6:Y:X	4:Y:X	1:N:O	
16	7	Y	9:N:X	1:Y:O	10:N:X	8:Y:O	4:Y:O	
17	8	N	8:N:O	5:N:O	4:Y:X	10:Y:X	10:N:O	
18	9	Y	2:Y:O	3:Y:O	3:Y:O	2:Y:O	6:N:X	
19	TOTAL CORRECT:	X%	80%	90%	70%	80%	70%	
20								
21								

figure.16: Example of spreadsheet used in final data collection

in order to mitigate the possibilities of motion sickness that has been associated with movement within virtual environments as well as to ensure that each participant experienced roughly the same aspects of the space. It was intended that they use this observational stage in the study to observe and memorize as much of the space as they can. Instructions were only provided if a glitch or bug is encountered in the program or if the user is interacting with the program in a method outside the scope of it’s intended use. If a glitch or bug caused an interference with the integrity of the simulation, the program was stopped and the timer was also stopped. The user were also asked to not remove the head mounted display while the researcher relaunched the program, this was effective for all issues with the simulation that occurred over the course of the study. Once relaunched the timer was resumed from the point at which the bug occurred and continued until the subject had completed their observation period. Any instance of a program being restarted has been noted on that user's results and included in the final reporting of the results. If during the observation period, the user had begun to interact with the simulation in an unintended way such as refusing to look around or discovering and exploiting unforeseen aspects of the program they would have been instructed to look around the environment as they would in the real space and to avoid the problematic behavior for the remainder of the study. If the participant had refused at that point, they would have been asked to leave and their results would have been removed from the study. Should any user have begun to feel nauseous or felt the onset of simulator sickness they would have been removed from their current environment and excluded from any proceeding environments. They would have also had any results associated with uncompleted environments removed from the study. Results from completed simulations would have been logged and included with a note indicating their removal from the study due to adverse reactions to the virtual environment.

Phase 3

Once the observational stage had been completed the Oculus Rift was returned to sleep mode and the user had been asked to remove their head mounted display, without altering the configurations made during the set-up procedures and to set the device aside for the time being.

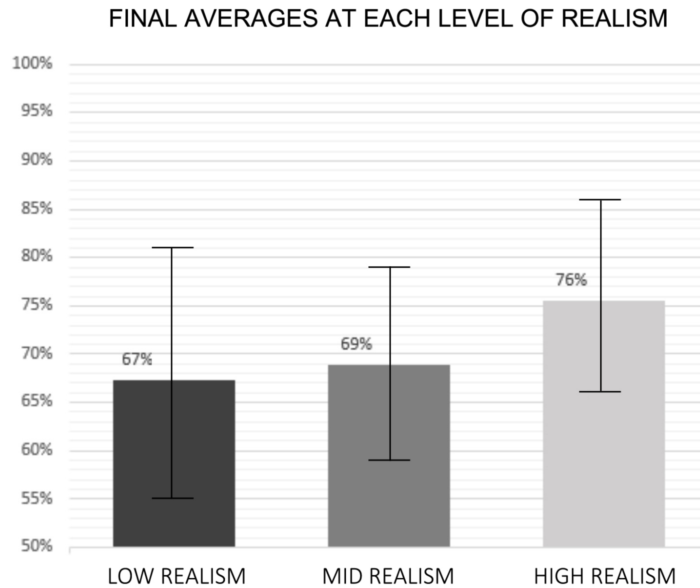
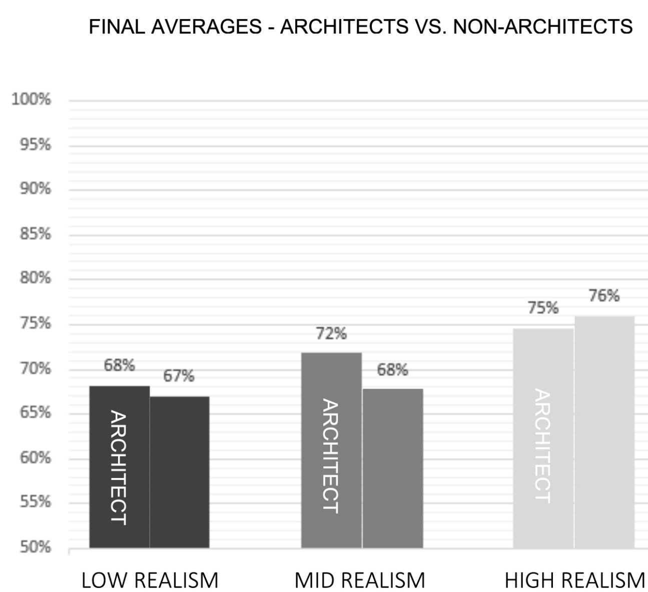


figure.17: Final averages at each level of realism.

figure.18: Final averages - Architects vs. non-architects



This was to allow the researchers to seamlessly move into the next environment without the need for further set-up time. After the participant is removed from the environment they are once again given the instructions on the procedures for the question phase of the study and what does and does not indicate a change between the images and the Oculus environment. The question phase then began once they indicated their readiness to proceed. The question phase was conducted by using the laptop monitor to display a series of images which may or may not be altered from the environment they were present in. The laptop monitor is a completely separate machine from the one that runs the virtual environments in order to ensure the smooth operation of the Oculus during the time which the participant is interacting with the space. The participant then gave a positive or negative response as to whether or not the image accurately represents the space they just experienced. The three image series are composed of ten images, five of which have alterations and five of which do not. These images are displayed in a random order but all images will be shown to each participant in order to eliminate variables associated with showing different images to different participants. The images have also been rendered to reflect the same level of realism as the environment which the participant was just removed. Each image has been rendered from a distinct camera angle rather than from the point of view which the participant experienced. Since this study is designed to test spatial memory rather than visual memory the separate camera angles are chosen to show the space and test how well the participant has understood the space through their experience with the Oculus. Varying the camera angle of the images forces the subject to reorient themselves in the space and make evaluations. The images have been designed to display a varying level of subtlety and each series has images that are obviously wrong and a few that are more difficult. The changes to the image are limited to geometric changes to the space or objects within the space, for example the curved roof has been flipped to face the other direction or there may be additional chairs placed in the scene.

Each image is displayed on the screen and the participants are asked to respond positively or negatively as quick as possible. Once the participant has indicated that they are ready to proceed with the questions the researcher then began to flip through the images one at a time, the researcher would only proceed to the next image once a definite positive or negative response had been attained. The researcher then records the responses to each image as they were given by the participant. Once the question phase had been completed the researcher then instructed the participant to return to the Oculus Rift and they were then placed into the second environment and the preceding steps will be repeated. The researcher then continued the steps until the participant has been moved through each of the remaining environments until the study has been concluded. Results of each study are then recorded in a spread sheet where they are tallied and compiled then compared before conclusions are drawn.

Observations During Study

Before the study began, participants were collected through fliers posted in the architecture halls, engineering buildings, libraries and computer science buildings on the University of Washington Campus as well as several e-mail lists composed of technology or architectural students on campus. Several in class announcements were also made by professors, letting students know that the study was being conducted. Participants during the study were mostly taken from outside the Department of Architecture, which was unexpected but positive because it allowed the research to compare the results of architecture students with students of different background. With few exceptions this was the first experience most of them had with the Oculus or virtual reality in general, and many subjects indicated that their interest in virtual reality was their primary reason for participating in the study. The two largest groups of students during the study were Architecture majors and Human Centered Design and Engineering majors, with computer science majors being the third most interested group of participants. A majority of the participants were also female. The methods we used to collect subjects also tended to collect more graduate students than undergraduate students. Of the methods we utilized, the mailing lists and word of mouth were most effective way of collecting subjects.

The first five subjects were used to test the method and procedures of the experiment to determine what needed to be altered about the study before proceeding to collect data for the final results. These initial five were given the original introductory script and testing images and during the presentation of the images were asked to identify the changes made to the images before giving their final answer. The identification of changes before answering was asked during the initial testing to ensure that the correct differences were able to be identified and that things that were not differences were not being identified as differences. The largest issue identified during this initial testing was that the colors and brightness of medium detail images were too distinct from the Oculus environment and were causing participants to be confused and answer incorrectly. These images were retouched and made to more closely resemble the Oculus environment. Once this change had been made the result of this image set began to be more reliable. The initial test subjects were not originally told what kind of changes would be made to the images but once test subject began identifying rendering differences and changes it was decided to add the explanation of what kind of changes would be made before the testing began in order to ensure subjects would not identify the wrong type of changes during the first environment and learn the correct changes on subsequent

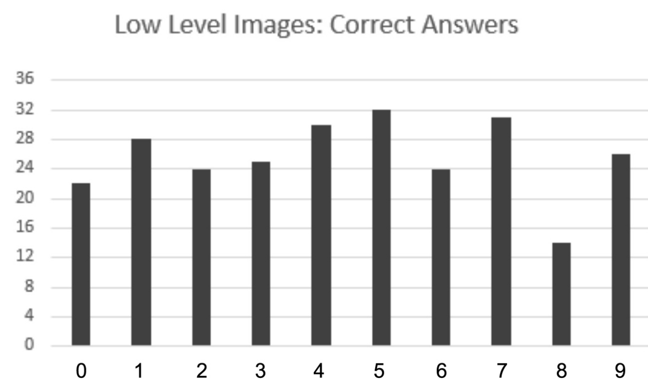


figure.19: Low Level Images: Correct Answers.

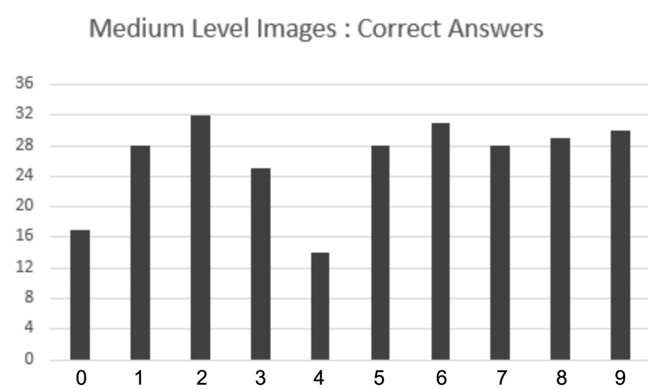
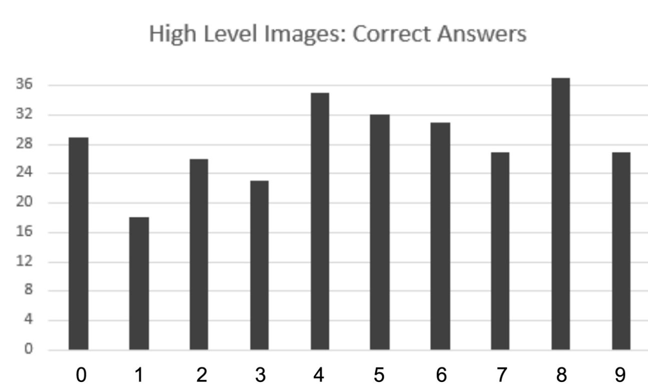


figure.20: Medium Level Images: Correct Answers.

figure.21: High Level Images: Correct Answers.



environments. The initial subjects all noted that the task was difficult but they scored highly when final results were taken so no changes were made to the difficulty of the questions being asked. The results also did not show a specific question getting no correct answers from the respondents, so there did not appear to any issues with any specific questions in the series. The testing questions required response was changed during this period of testing. Originally the test required participants to say “yes” if the image reflected the Oculus environment and “no” if it did not. This confused several participants and was changed to “same” or “different” to ensure that subjects would not be confused about the content of their answer.

Overall the test ran very smoothly, and during the testing there were very few issues with the simulations that caused them to be restarted. There were three instances of the simulation not starting correctly where the users saw a blank screen or noise pattern at launch. All of these instances were fixed by a quick restart of the simulation. The only other problem that occurred during testing was that one participant complained that the simulation was blurry when I launched the environment, so the simulation was paused, and the lenses were cleaned. This solved the problem. All of the feedback that I received from participants after the testing was complete was very positive about the experience within the Oculus. Most remarked about how well the virtual reality environment was able to convey space and how immersive it felt to be in the environment in virtual reality. A few subjects thought that the lack of a representative body made them feel like they were floating. A number of subjects thought that it felt awkward because of that but none of them felt negatively about the experience as a whole because of it. This feeling was also amplified because the camera in the simulation is positioned at standing height rather then the sitting position that the subjects are physically experiencing the test in. The disconnect between their body position and virtual position may have increased this effect. There were no cases of simulation sickness during the testing, although one person remarked after the testing that she thought it may have become too uncomfortable if she had been in the simulation for very much longer, and a few of the subjects stated that they began to feel dizzy if they moved their head very quickly in the medium or high detail models. The low quality model ran at a very high framerate and no one had comfort issues with this simulation, but the two more detailed environments were much more processing intensive making them run at a slightly lower framerate. Some people commented about the lower frame rate. No one was uncomfortable enough in the simulation to stop, and most were just making the observation. Almost all of the participants, when asked, stated that they felt very comfortable looking around and interacting with the simulation. There were no cases of a test being stopped due to discomfort.

The results of the testing seemed to reflect the results of the initial tests, with most subjects scoring higher on the high levels of realism. Most

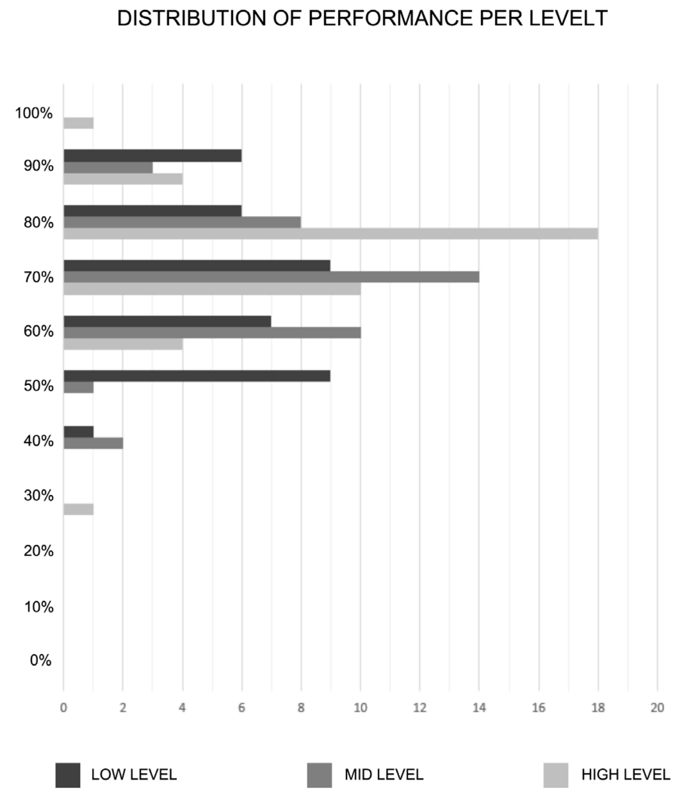


figure.22: Distribution of Performance per Level

commented that the test was very difficult but once the results were tallied their scores were relatively good and there were no obvious problem questions that everyone got wrong. The varying level of difficulty of the questions meant that there were a few difficult questions that few participants answered correctly, but the data seemed to show a similar distribution of difficult questions between each simulation. Despite telling participants that I were not required to describe any alterations made to the testing images, most talked through the images to themselves and described the problems with the images accurately. There were only a few instances where the problems identified in the altered testing images, did not match with the actual alterations made to the image for the negative response. At the end of testing 38 participants were tested and none of these subjects had to have their results discarded or partially recorded due to issues during the study. During the testing we also asked the participants whether they had architectural experience, ether in their education or professionally, and recorded their responses, to determine whether their experience and memory of the spaces would be impacted in any significant way by their architectural background.

Analysis of Data

The result of the testing seems to reinforce the original hypothesis that the study was operating from: that the higher level of detail in the Oculus model would result in a greater retention of spatial information from the experience of the space within the Oculus. Of the 38 participants in the study 11 of them identified themselves as having had an architectural background or training. Since each testing section had an even distribution of changed an unchanged images, the subjects had a 50% chance of guessing the correct answer. This was the baseline to determine whether or not the experience in the virtual environment had an impact on the memory of the participants, and the data that was collected seemed to reflect that, even at the lowest level of detail.

The lowest level of detail had the lowest impact on the ability for the subjects to accurately identify changes to the space in the image testing but participants still scored 17% above random (60% and above) in the low level of realism. The architectural group and the non-architectural group performed almost identically on this stage of rendering, with architects averaging 68% correct responses while the non-architects averaged 67%. There were no images that all of the participants were able to correctly identify whether changed or unchanged. The lowest level of realism saw the largest variation in performance of any of the environments with participants' scores being fairly evenly distributed within the 50-90% range with most participants scoring ether 50% or 70%. Only one participant in this group scored lower than random, and 74% of participants scored better than random indicating that their experience of the space in virtual reality had an impact on their memory of the space. There were no participants who received a perfect score of 100% on this level of realism. The highest performing questions were the unchanged images, which is a good indication that the image composition and camera position was not a significantly distracting element when trying to determine whether an image had been changed or not. This would continue to be a trend as the study moved to higher levels of realism. This data also seemed to be unaffected by the order in which it was presented to the subjects. The predicted variation of the designed difficulty in the questions also matched the data with the

figure.23: Oculus Rift in operation.

most recognizable changes in the images scoring very high, while the more subtle questions scored significantly lower. The lowest scoring question was image number eight, which was an altered image where the table legs had been removed from the tables in the cafe area; this was also the image in this set designed to be the most difficult. This image was only recognized correctly as an altered image 37% of the time. The most correctly identified altered image was also the image designed to be the simplest to recognize and was correctly identified by 79% of participants.

The environment representing the medium level of realism, which added lighting to the previous simulation, saw an almost negligible improvement over the previous environment with participants able to correctly identify alterations to the space an average of 69% of the time. This stage of the experiment saw a slight variation between the performance of architects and their non-architect peers. The non- architects on this environment were able to correctly identify the images 68% of the time while those who identified as architects were able to correctly respond to the questions 72% of the time. This puts the non-architect scores at a nearly equivalent level to their performance on the low level of realism indicating that there was no significant increase in spatial memory retention for non-architects when transitioning from an untextured space and ambiently lit space to an untextured and realistically lit space. This level of realism had significantly less variation in the performance of subjects when compared to the low realism environment, with 64% of subjects scoring ether a 60% or 70% and 92% of subjects scoring better then random. The Image questions worked similarly to the previous level of realism with the difficult questions scoring lowest while the most simple changes were easily recognized by the subjects. However, one altered image that had been designed to be simpler to identify did score lower than expected. The image that had been altered to show two candles on the cafe tables, proved to be difficult for subjects to identify with only 45% of subjects able to correctly identify the image as changed. The unaltered Oculus space only had a single candle on each table. Other than that anomaly in the questions the distribution of correct answers was very similar to the previous environment. Once again, there were no instances of perfect scores for the medium level of realism.

The simulation with the highest level of realism saw the greatest increase in performance in the experiment. The lowest level of realism averaged 67% correct responses from participants while the highest level of realism averaged 76% correct responses from subjects. Similar to the lowest level of realism, the architect group and non-architect group performed virtually the same, with the subjects identifying as architects correctly answering 75% of questions correctly and non-architects answering 76% of questions correctly. This level of realism also had the most consistent scores of the experiment, with 74% of participants scoring a 70% or 80% on the questions, a significant majority of which scored 80% (47% of participants). This level also had the highest percentage of subjects who scored higher than random, with only a single subject who performed below random, which scored the participants at 97% above random. The questions, much like the first level performed as expected with the lowest scoring altered image being image number one, which altered the wavy ceiling portion of the space to be significantly taller than the experience of the space in Oculus. This question was correctly identified as altered by 47% of participants. This was the only level that had a participant achieve a perfect score during the question period.

Conclusions from Data

The relatively small subject pool and wide range of scores between participants has left the study with a wide deviation in the answers, particularly in the lower stages of realism, and therefore it cannot be conclusively stated that increase in the level of realism within the virtual environment has a significant impact on the spatial memory of those who experience it, despite the scores seeming to indicate as much during the course of the study. The numbers gathered during this study indicate the there is a trend that the more realistic the space is the better spatial memory retention is gained, but significantly more testing would have to be conducted to narrow the deviation, and a majority of subjects did perform better on the highest stage of realism than they did on the lowest. The test was still able to illustrate that experiencing the space through virtual reality does have an impact on the spatial memory of participants, with 88% of all test subjects performing above random, which indicates that spatial learning is taking place while subjects experience the space virtually. Even factoring in the deviation, still puts the final averages above random and therefore indicative of assisting in the formation of spatial memory. If the study was scaled up the outliers that may be affecting the deviation of study may be less impactful, and the trend may become more clear.

Without taking into account deviation, the difference between performance between the lowest level and the highest level of realism lands at almost a 10% increase in performance. Although not a massive change this still shows a jump in peoples ability to read and understand the space when materials and lighting were introduced to the scene. In fact, many users who experienced the textured environment after experiencing the two lower realism space expressed this feeling while taking the test. They felt that they were able to ground themselves more and read the space more clearly. The introduction of lighting seemed to have almost no effect on people's ability to read the space, as opposed to the lowest level of realism. Even without considering the deviation the difference is only 2% making the medium level a negligible change in the progression of spatial awareness.

Though the number of subjects does not make this statistically significant, the architectural background of the subjects did not seem to have a significant effect to the performance of the subjects on the task. The medium level images were the only place where variation occurred, and even then only indicated a 4% improvement in performance. Both of the other levels of realism were within 1% of each other indicating that there was no difference in the ability to build spatial memory through virtual reality compared to non-architects.

Moving the Study Forward

The purpose of this study was to provide an outline and framework for a larger more substantive study that built upon the conclusions of this study. Moving forward the largest thing that would need to be scaled up from the original study is the sample size. While we were able to reach a number deemed statistically significant, it failed to return much concrete difference between the performance on the different levels of realism. With a larger sample size the trend of higher performance on higher levels of detail, if there truly is one once scaled up, could be more defined and articulated. It would also allow for the conclusions drawn about the significance of the architectural background on the task to be tested. The sample of subjects tested should also expand to more subjects outside of the university and preferably into the profession in order to draw conclusions about the clients. The subject backgrounds also should be more varied in any future expansions of this study. The wide majority of the subjects were college age and majoring in technology focused areas. Despite almost none of the participants having direct experience with virtual reality, there was a small minority that did have some prior experience. On any future iteration of the study some indication should be noted as to whether or not the participant has any experience in gaming or 3D modeling, which may also sway their ability to process information in a virtual environment. The larger subject pool would also allow us to draw conclusions about how the order of both the images and the order of the simulations affect their ability to perform on the test.

The other largest element of the study that needs additional finesse for a larger study in the future is some additional research on the effectiveness of the chosen images. While there was nothing in the test to indicate that any of the images were a problem for this study, on a larger scale it may be helpful to do a few rounds of testing on just the images themselves to weed out any unforeseen variables that could be causing people to miss questions for reasons separate from their spatial recall.

With a larger subject pool the most significant change that should be made is that each subject should only experience one level of realism. The main reason that it was decided to show all subjects all three levels of realism was to compensate for the short time frame and relatively small subject pool that dictated how the study would proceed. With a larger time frame and greater amount of participants the ability to use one subject per level would be much more viable. This would eliminate any sort of issues related to learning immediately. Though this didn't seem to be an issue with the current iteration of the study the ability to eliminate variables where possible is always a positive. Showing a single level of realism per subject would also allow the altered images to be more consistent between levels of realism and allow more concrete data to be gained about exactly what kind of spatial changes are easier to identify at different levels of realism in addition to the gross averages that this test was able to produce.

Conclusion

The study was able to establish a trend that higher levels of detail do seem to have an impact on the spatial memory of those who experience a space in virtual reality but will require more subjects to provide a definitive answer on the degree to which that may be true. Spatial memory has been affected by the use of virtual reality as exemplified by participant's regular ability to perform at a level higher then random, even at the lower levels of realism. This seems to indicate that virtual reality can be an effective tool for conveying architectural ideas even at lower levels of realism. Higher levels of realism while visually impressive and show a jump in the occupant's spatial processing, are not required to receive at least some benefits to spatial understanding provided by virtual reality. The implications of this seem to indicate that even at earlier stages of design, virtual reality has benefits to helping users understand space regardless of their experience or education. With an increase in scale the test itself could give a clearer quantification of the degree in which our perception and understanding of space in virtual reality is effected by the realism of the simulated environment.

BIBLIOGRAPHY

Abdelhameed, Wael. (2014) “Creativity in VR Use - A Case Study.” in CAADRIA 2014 719-28.

Achten, Henri, Joran Jessurun, Bauke de Vries. (2004) “A Low-Cost Versatile Virtual Reality Design and Research Setup Between Desktop and CAVE” in Architecture in the Network Society [22nd eCAADe Conference Proceedings], 142-147.

Adams, Will. (2013) “Spatial Cognition in Virtual Reality: Developing an Evaluation Technique for Representational Methods of Virtual Models.” in MSRP Fall 2013 [Research Project Will Adams] 1-12.

Al-Attili, Aghlab, and Maria Androulaki. (2009) “Architectural Abstraction and Representation: The embodied familiarity of digital space.” in Digitizing Architecture: Formalization and Content, [4th International Conference Proceedings of the Arab Society for Computer Aided Architectural Design] 305-321.

Angulo, Antonieta, and Guillermo Vásquez de Velasco. (2014) “Immersive Simulation in Instructional Design Studios.” in Blucher Design Proceedings 1, no. 8. 236-240.

Ângulo, Antonieta, and Guillermo Vásquez De Velasco. (2013) “Immersive Simulation of Architectural Spatial Experiences.” in SIGraDi: Knowledge-based Design, no. 2013 [Proceedings of the XVII Conference of the Iberoamerican Society of Digital Graphics] 495-99.

Allen, Gary L., and Daniel BM Haun. (2004) “Proximity and precision in spatial memory.” in Human spatial memory: Remembering where. 41-63.

Araújo, Bruno, Joaquim Jorge, and José Duarte. (2012) “Combining virtual environments and direct manipulation for architectural modeling.” in Proceedings of eCAADe 2012. 419-428.

Ardouin, J., A. Lecuyer, M. Marchal, and E. Marchand. (2014) “Stereoscopic Rendering of Virtual Environments with Wide Field-of-Views up to 360°.” in Virtual Reality (VR) [2014 IEEE] 3-8.

Arthur, E. J., P. A. Hancock, and S. T. Chrysler. (1997) “The perception of spatial layout in real and virtual worlds.” in Ergonomics 40, no. 1. 69-77.

Avila, Lisa, and Mike Bailey. (2014) “Virtual Reality for the Masses.” in Computer Graphics and Applications [IEEE Volume 34, no. 5] 103-04.

Billger, Monica, and Stefano d’Elia. (2002) “Color appearance in virtual reality: a comparison between a full-scale room and a virtual reality simulation.” in 9th Congress of the International Color Association, [International Society for Optics and Photonics, 2002] 122-126.

Bolas, M., P. Hoberman, Thai Phan, P. Luckey, J. Iliff, N. Burba, I. McDowall, and D.M. Krum. (2013) “Open Virtual Reality.” in Virtual Reality (VR), [2013 IEEE, no. 978-1-4673-4795-2] 183-84.

Burgess, Neil, and John O’Keefe. (2003) “Neural representations in human spatial memory.” in Trends in cognitive sciences 7, no. 12. 517-519.

Boukerche, Azzedine, Abdulaziz Al Hamidi, Richard Pazzi, and Luqman Ahmad. (2009) “Architectural design for the 3D virtual Radiology Department using Virtual reality technology.” in Computational Intelligence in Virtual Environments [CIVE’09. IEEE Workshop on] 45-52

Encyclopædia Britannica Online, s. v. “virtual reality (VR)”, accessed March 15, 2016, http://www.britannica.com/technology/virtual-reality.

Brooks, B. M., F. D. Rose, J. Potter, S. Jayawardena, and A. Morling. (2004) “Assessing stroke patients’ prospective memory using virtual reality.” in Brain Injury 18, no. 4. 391-401.

Bruder, G., and F. Steinicke. (2014) “Time Perception during Walking in Virtual Environments.” in Virtual Reality (VR) [IEEE, 2014] 9-14.

Burgess, Neil, Suzanna Becker, John A. King, and John O’Keefe. (2001) “Memory for events and their spatial context: models and experiments.” in Philosophical Transactions of the Royal Society of London B: Biological Sciences 356, no. 1413. 1493-1503.

BIBLIOGRAPHY

Chun, Marvin M., and Yuhong Jiang. (1998) “Contextual cueing: Implicit learning and memory of visual context guides spatial attention.” in Cognitive psychology 36, no. 1. 28-71.

Cobb, Sue VG, Sarah Nichols, Amanda Ramsey, and John R. Wilson. (1999) “Virtual reality-induced symptoms and effects (VRISE).” in Presence 8, no. 2. 169-186.

Creem-Regehr, Sarah H (2004) “Remembering Spatial Locations: 163 The Role of Physical Movement in Egocentric Updating” in Human spatial memory: Remembering where. [Psychology Press] 163-190

Dinh, Huong Q., Neff Walker, Larry F. Hodges, Chang Song, and Akira Kobayashi. (1999) “Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments.” in Virtual Reality, [Proceedings., IEEE] pp. 222-228

Dünser, Andreas, Karin Steinbügl, Hannes Kaufmann, and Judith Glück. (2006) “Virtual and augmented reality as spatial ability training tools.” in Proceedings of the 7th ACM SIGCHI New Zealand chapter’s international conference on Computer-human interaction: design centered HCI, [ACM] 125-132.

Febretti, Alessandro, Arthur Nishimoto, Victor Mateevitsi, Luc Renambot, Andrew Johnson, and Jason Leigh. (2014) “Omegalib: A multi-view application framework for hybrid reality display environments.” In Virtual Reality (VR) [2014 iEEE] 9-14

Gallagher, Anthony G., E. Matt Ritter, Howard Champion, Gerald Higgins, Marvin P. Fried, Gerald Moses, C. Daniel Smith, and Richard M. Satava. (2005) “Virtual reality simulation for the operating room: proficiency-based training as a paradigm shift in surgical skills training.” in Annals of surgery 241, no. 2. 364-372.

Gillner, Sabine, and Hanspeter A. Mallot. (1998) “Navigation and acquisition of spatial knowledge in a virtual maze.” in Journal of Cognitive Neuroscience 10, no. 4. 445-463.

Gould, Neda F., B. S. M Kathleen Holmes, Bryan D. Fantie, David A. Luckenbaugh, Daniel S. Pine, Todd D. Gould, Neil Burgess, Husseini K. Manji, and Carlos A. Zarate Jr. (2007) “Performance on a virtual reality spatial memory navigation task in depressed patients.” in American Journal of Psychiatry 516-518

Freund, Eckhard, Juergen Rossmann, and Marcel Brasch. (2001) “Open multi-agent control architecture to support virtual-reality-based man-machine interfaces.” in Intelligent Systems and Advanced Manufacturing, [International Society for Optics and Photonics] 219-229

He, Yifeng, Ziyang Zhang, Xiaoming Nan, Ning Zhang, Fei Guo, Edward Rosales, and Ling Guan. (2014) “vConnect: Connect the real world to the virtual world.” in Computational Intelligence and Virtual Environments for Measurement Systems and Applications (CIVEMSA), 2014 [IEEE International Conference on,] 30-35.

Lin, James Jeng-Weei, Henry BL Duh, Donald E. Parker, Habib Abi-Rached, and Thomas A. Furness. (2002) “Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment.” in Virtual Reality, 2002. [Proceedings. IEEE,] 164-171

Kalarat, Kosin. (2014) “Relief Mapping on Facade of Sino Portuguese Architecture in Virtual Reality.” in Digital Information and Communication Technology and it’s Applications [(DICTAP), 2014 Fourth International Conference on,] 333-336

Kolasinski, Eugenia M. (1995) Simulator Sickness in Virtual Environments. No. ARI-TR-1027. ARMY RESEARCH INST FOR THE BEHAVIORAL AND SOCIAL SCIENCES ALEXANDRIA VA,

Schlickum, Marcus Kolga, Leif Hedman, Lars Enochsson, Ann Kjellin, and Li Felländer-Tsai. (2009) “Systematic video game training in surgical novices improves performance in virtual reality endoscopic surgical simulators: a prospective randomized study.” in World journal of surgery 33, no. 11. 2360-2367

Komianos, V., E. Kavvadia, and K. Oikonomou.(2014) “Efficient and Realistic Cultural Heritage Representation in Large Scale Virtual Environments.” in Information, Intelligence, Systems and Applications, [IISA 2014, The 5th International Conference on,] 1-6.

Kreutzberg, Anette. (2014) “New Virtual Reality for Architectural Investigations.” in ECAADe 2, no. 32, 253-60.

Lewis-Evans, Ben. (2014) “Simulation Sickness and VR What Is It, and What Can Developers and Players Do to Reduce It?” in Gamasutra [http://www.gamasutra.com/blogs/BenLewisEvans/20140404/214732/Simulation_Sickness_and_VR__What_is_it_].

Maleshkov, Stoyan, and Dimo Chotrov. (2013) “Affordable Virtual Reality System Architecture for Representation of Implicit Object Properties.” in arXiv preprint arXiv:1308.5843

Mania, Katerina, and Alan Chalmers. (2001) “The effects of levels of immersion on memory and presence in virtual environments: A reality centered approach.” in CyberPsychology & Behavior 4, no. 2. 247-264.

McNamara, T. P., and Christine M. Valiquette. (2004) “Remembering where things are.” in Human spatial memory: Remembering where 251-285.

Moffat, Scott D., Alan B. Zonderman, and Susan M. Resnick. (2001) “Age differences in spatial memory in a virtual environment navigation task.” in Neurobiology of aging 22, no. 5 787-796

Montello, Daniel R., David Waller, Mary Hegarty, and Anthony E. Richardson. (2004) “Spatial memory of real environments, virtual environments, and maps.” in Human spatial memory: Remembering where 251-285.

Morris, Robin G., and David M. Parslow. (2004) “Neurocognitive components of spatial memory.” in Human spatial memory: Remembering where 217-247.

Optale, Gabriele, Cosimo Urgesi, Valentina Busato, Silvia Marin, Lamberto Piron, Konstantinos Priftis, Luciano Gamberini, Salvatore Capodieci, and Adalberto Bordin. (2010) “Controlling memory impairment in elderly adults using virtual reality memory training: a randomized controlled pilot study.” in Neurorehabilitation and neural repair 24, no. 4 348-357.

Oman, Charles M., Wayne L. Shebilske, Jason T. Richards, Travis C. Tubré, Andrew C. Beall, and Alan Natapoff. (2000) “Three dimensional spatial memory and learning in real and virtual environments.” in Spatial Cognition and computation 2, no. 4 355-372.

Parsons, Thomas D., and Albert A. Rizzo. (2008) “Initial validation of a virtual environment for assessment of memory functioning: virtual reality cognitive performance assessment test.” in CyberPsychology & Behavior 11, no. 1 17-25

Parslow, David M., David Rose, Barbara Brooks, Simon Fleminger, Jeffrey A. Gray, Vincent Giampietro, Michael J. Brammer et al. (2004) “Allocentric spatial memory activation of the hippocampal formation measured with fMRI.” in Neuropsychology 18, no. 3 450

Patel, Navinchandra K., Simon P. Campion, and Terrance Fernando. (2002) “Evaluating the Use of Virtual Reality as a Tool for Briefing Clients in Architecture.” in Information Visualisation, 2002. [Proceedings. Sixth International Conference on 1093-9547, no. 0-7695-1656-4] 1-7.

Pint, Kris. (2012) “The Avatar as a methodological tool for the embodied exploration of virtual environments.” in CLCWeb: Comparative Literature and Culture 14

Ponto, K., Chen, K., Tredinnick, R. and Radwin, R.G. (2014) “March. Assessing Exertions: How an increased level of immersion unwittingly leads to more natural behavior” in Virtual Reality (VR), [2014 iEEE] 107-108

Postma, Albert, Roy PC Kessels, and Marieke van Asselen. (2004) “The neuropsychology of object-location memory.” in Human spatial memory: Remembering where 143-160.

Rizzo, Albert, and J. Galen Buckwalter. (1997) “Virtual Reality and Cognitive Assessment and Rehabilitation: The State of the Art” in G. Riva (Ed), Virtual Reality in Neuro-Psycho-Physiology [IOS Press, Holanda]

Sato-Wang, Reika. (2006) “Cognitive Psychological For Urban Plan & Architecture Using the Virtual Reality System.” in Systems, Man and Cybernetics, 2006. [SMC ‘06. IEEE International Conference on 3] 2045-2050.

Schulze, Jürgen P., Cathleen E. Hughes, Lelin Zhang, Eve Edelstein, and Eduardo Macagno. (2014) "CaveCAD: a tool for architectural design in immersive virtual environments." in IS&T/SPIE Electronic Imaging [International Society for Optics and Photonics] 1-10

Schumann-Hengsteler, Ruth, Martin Strobl, and Christof Zoelch. (2004) "Temporal Memory for Locations: On the Coding of Spatiotemporal Information in Children and Adults." in Human spatial memory: Remembering where. 101-124

Schuwerk, Clemens, Rahul Chaudhari, and Eckehard Steinbach. (2014) "Delay compensation in shared haptic virtual environments." in Haptics Symposium [(HAPTICS), 2014 IEEE] 371-377

Shelton, Amy Lynne (2004) "Putting Spatial Memories Into Perspective: Brain and Behavioral Evidence for Representational Differences" in Human spatial memory: Remembering where. Psychology Press, 2004.

Sheng, Wang, S. Nakata, S. Tanaka, H. H. Tanaka, and A. Tsukamoto. (2013) "Modeling High-Quality and Game-Like Virtual Space of a Court Noble House by Using 3D Game Engine." in Culture and Computing [(Culture Computing), 2013 International Conference on,] 212-13.

Spiller, Neil (2000) "Mixing the real and the virtual" in Architect's Journal.

Su, Ping, and Shuo Wang. (2012) "Virtual Reality Practice in Architecture Design." in Electrical & Electronics Engineering (EEESYM), 2012 [IEEE Symposium on, no. 978-1-4673-2363-5] 98-101.

Tahrani, S., G. Moreau, and Nantes Cerma Ensa. (2007) "Analyzing Urban Daylighting Ambiences by Walking in a Virtual City." Virtual Reality Conference, 2007. VR '07. IEEE, 2007] 227-30.

Thomas,, J., R. Bashyal, S. Goldstein, and E. Suma. (2014) "MuVR: A Multi-User Virtual Reality Platform." in Virtual Reality (VR) [IEEE, 2014] 115-16.

Waller, David, Earl Hunt, and David Knapp. (1998) "The transfer of spatial knowledge in virtual environment training." in Presence 7, no. 2. 129-143

Webel, S., M. Olbrich, T. Franke, and J. Keil. (2013) "Immersive Experience of Current and Ancient Reconstructed Cultural Attractions." in Digital Heritage International Congress [DigitalHeritage, 2013 1] 395-398

Weniger, Godehard, Mirjana Ruhleder, Claudia Lange, Stefanie Wolf, and Eva Irle. (2011) "Egocentric and allocentric memory as assessed by virtual reality in individuals with amnestic mild cognitive impairment." in Neuropsychologia 49, no. 3. 518-527

Xia, Liu, and Qiao Jiangang. (2008) "Research on Chinese Museum Design Based on Virtual Reality." in Modelling, Simulation and Optimization, 2008. [WMSO '08. International Workshop on Volume 3] 372-74

Yuan, Kun, Dong Yang, and Yumei Cui. (2012) "Application of virtual reality technology in the space teaching of Landscape Architecture." in Information Technology in Medicine and Education [(ITME), 2012 International Symposium on, vol. 1.] 375-378

Zielinski, David, Brian Macdonald, and Regis Kopper. (2014) "Comparative study of input devices for a VR mine simulation." in Virtual Reality (VR) [2014 iEEE] 125-126