Experience Before Construction: Immersive Virtual Reality Design Tools for Architectural Practice

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Abstract

In architectural design, understanding and communicating how a building will be experienced is an ongoing challenge. However, recent developments in Immersive Virtual Reality (IVR) technology are revealing a new design representation tool capable of providing realistic experiences of computer-generated spaces. Still, the question of how such design representation tools should be designed is a subject of ongoing debate. Here we first outline potential usage scenarios and system requirements based on interviews and focus groups with practicing architects, then describe how this information was used to inform the design of a foundational IVR representation interface that encompasses these scenarios and requirements, and lastly experimentally evaluated the interface according to the system requirements outlined initially. Our findings indicate that our embodied interface provided users with an immersive experience of the space without requiring a significant investment of set up time. Finally, design lessons and future design goals of our interface are discussed.

Keywords: Architecture; Design Representation; Immersion; Virtual Reality; Locomotion; Spatial Orientation

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But most importantly, I'm thankful to my Mom, for taking care of me when I was young, and allowing me to return the favor now that I'm old.

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List of Acronyms

2D	Two Dimensional
3D	Three Dimensional
AEC	Architecture, Engineering, and Construction
BIM	Building Information Modeling
CAD	Computer Aided Drafting
DOF	Degrees of Freedom
FPS	Frames Per Second
HMD	Head Mounted Display
IVR	Immersive Virtual Reality
VE	Virtual Environment

Glossary

Architectural Design Review	a process for evaluating the aesthetic effects of the physical attributes of environmental projects (Stamps, 1994).
Architectural Practice	a professional discipline addressing the forms and images of human habitat, the processes of its invention, its constructive technology, and its material fabrication; comprised of architects, designers and non-design staff; as a domain it has its own internal conventions of representation, judgment, and composition (Wasserman, Sullivan, & Palermo, 2000).
Building Information Modeling (BIM)	the development and use of a computer software model to simulate the construction and operation of a facility. The resulting model is a data rich, object oriented, intelligent and parametric representation of the facility from where views and data appropriate to various users' needs can be extracted and analysed to generate information that can be used to make decisions and improve the process of delivering the facility (Boon, 2009).
Design	the intellectual conception of a manufactured or constructed object prior to its production (Goldschmidt & Porter, 2004).
Immersion	a quality of a technology used to make a user feel present in the virtual environment (Slater & Wilbur, 1997).
Presence	a state of consciousness that may be concomitant with immersion, and is related to a sense of being in a place (Slater & Wilbur, 1997).
Representation	an abstracted symbolic testing of the results of the conceptual process of design (Goldschmidt & Porter, 2004).
Usability	a quality attribute that assesses how easy a user interfaces is to use; also refers to methods for improving ease-of-use during the design process by maximizing learnability, efficiency, memorability, and satisfaction, while minimizing errors (Nielsen, 1994).
User Experience Design	the creation and synchronization of the elements that affect users' experience with a particular company, with the intent of influencing their perceptions and behavior (Unger & Chandler, 2012).
Virtual Reality	a technology that grants a user a means of interaction with an environment simulating reality, or interaction with an imaginary or symbolic world (Fuchs, Moreau, & Guitton, 2011).

Chapter 1. Introduction and Motivation

As humans, we are driven to change our world. We are compelled to mold it, to shape it, to redesign it. Sometimes we do so merely to survive, while other times we just want to make our lives easier. At times we wish only to impart beauty upon this earth, to create objects whose form and structure simply resonate within the human mind. However, when we experience a creation that fulfills each of these - our needs, wants, and our dreams - we see the highest expression of design. *-JF*

These words are particularly true in the field of architectural design. The task of designing and constructing a building that optimizes these factors is not a simple one, and will inevitably require the use of design representations (Visser, 2010). As simple as a black and white plan view, or as intricate as a 3D physical model, design representations can help a designer to focus thoughts and conversations regarding the design on specific areas in question.

While contemporary design representations bring important aspects of the design into focus, a representation that provides an immersive experience of the project is usually not available during the design process. However, the development of high quality affordable virtual reality technologies, along with increasing usage of digital design tools, present new opportunities for the use of Immersive Virtual Reality (IVR) as a representation form. These IVR technologies present users with a means of sensory interaction through an interface that typically mimics real world interaction, and initiates a sense of immersion where the user feels as though as though they are present in a virtual environment (VE) (Fuchs et al., 2011; Witmer & Singer, 1998). As the trend towards lower cost and higher quality IVR continues, it is increasingly possible that the very way that architecture is designed will dramatically change to incorporate these new representational capabilities. In turn, creating architecture that fulfills our criteria for outstanding design may become more attainable as a result.

Indeed, the future may be bright, yet there are many unanswered questions. In this thesis we focus on four specific research questions (RQ) directed towards the design of an IVR representation interface that can be useful in architectural practice:

RQ 1) What usage scenarios would architects want to use IVR for?

RQ 2) What are the system requirements of an IVR representation tool for different usage scenarios?

RQ 3) How can we design an IVR architectural representation interface that fulfills the system requirements for most of our usage scenarios?

RQ 4) How does our IVR architectural representation interface compare to existing interfaces?

To answer these questions we use a sequential mixed methods approach, in which we first qualitatively explored the potential of IVR in architectural practice with interviews and focus groups, using our findings to outline usage scenarios and requirements for an IVR system (phase 1). Following this we designed an IVR representation interface (phase 2) that responds to the scenarios and requirements from phase 1. Lastly we quantitatively evaluated the interface to assess the fulfillment of system requirements, to compare our design with existing interfaces, and finally to inform future development of IVR representation interfaces for architectural practice (phase 3).

These project phases are described in the following chapters, with Chapter 2 describing phase 1 (RQ 1 & RQ 2) and Chapter 3 describing phase 2 (RQ 3) and phase 3 (RQ 4). We then conclude in Chapter 4 with a broad discussion of the findings and limitations of our research, and then talk about the design of future IVR representation interfaces for architectural practice.

1.1. Scope and Delimitation

While the potential uses for IVR in architectural practice are extensive, this thesis first approaches the subject in very broad terms during phase 1, with scenarios discussed on how an IVR representation interface could be useful in practice and what the requirements of such an interface should be. Then in phase 2, we design and prototype an interface that fulfills the basic requirements for each scenario, and can be expanded to respond to each scenario in future development iterations. Lastly, in phase 3 we evaluate the interface in a future occupant testing scenario and investigate basic usability criteria, focusing primarily on issues of navigation performance, motion sickness, and a user's experience of sensory immersion, as well as gathering feedback on how the interface could be improved. By first evaluating and developing these core issues, we can provide a solid foundation for future development. Consequently, more specific scenarios that involve architects using the representation interface for design tasks, such as modeling or review, are not assessed in this thesis.

Chapter 2. Exploration of Immersive Virtual Reality in Architectural Design

In a number of design disciplines, interest has been growing in the use of Immersive Virtual Reality (IVR) during the spatial design process and subsequent presentation of a project. While the cost of the technology required for these design process tools has previously proven feasible only for design and engineering industries with large budgets (e.g., aerospace and automotive industries), IVR technologies are becoming increasingly available at lower costs. These recent developments are providing more design and engineering disciplines, such as architectural design, with the potential to create, explore, and experience projects using immersive design representation tools. Currently, the questions presenting themselves to these industries revolve around how to effectively integrate such interactive representation tools into competitive practice (Greenwood et al., 2008).

Design, especially architectural design, is only possible through representation (Goldschmidt & Porter, 2004). According to Visser (2006), design is actually defined as the act of constructing representations. This idea is particularly important in the field of architectural design, in which a representation is often used to gauge the experiential aspects of a design (Yaneva, 2005). Through representation the design can be communicated, both to oneself and to others (Goldschmidt & Porter, 2004). Traditionally, the most common representations in the field of architecture consist of two-dimensional plan, section, and elevation views, perspectival renderings, and three-dimensional physical models.

With the development of software based design tools such as two-dimensional Computer Aided Drafting (CAD), now being replaced by three-dimensional Building Information Modeling (BIM), entire projects are available in digital format. Although often more cost and effort intensive during the initial stages of design, these BIM design tools provide a data rich three-dimensional digital model that allows for automated construction document generation, easily generated perspective renderings, parametric design capabilities, simulations of building systems and environmental conditions, and a digital building model for use in future facilities management and renovation projects (Boon, 2009; Eastman et al., 2011).

Particularly with large datasets found in building systems and environmental conditions simulations, a vast amount of spatialized data becomes available for architects using these tools. This abundance of data can demand extensive cognitive resources from the designer and potentially obscures relationships between elements of the project during data exploration (Pressman, 2006; Ware & Franck, 1996).

Through IVR technologies, a user can improve their understanding of three-dimensional data and spatial relationships, as well as provide an immersive experience of the design, allowing the architect to assess the affective experience of the space (Riva et al., 2007; van Dam et al., 2002). Beyond this, the increasing prevalence of project design over distances may one day grant architects the ability to design and collaborate in IVR through telepresence, decreasing the need for travel and improving communication within a design team (Wojtowicz & Butelski, 1999). Additionally, a fully defined model can then be used in the construction process through augmented reality technologies, potentially reducing errors in construction and decreasing costly construction mistakes (Webster et al., 1996).

Although the future of IVR architectural design tools has yet to be determined, much research has been conducted in regards to specific approaches towards designing VR interfaces for the field of architecture. Ranging from architectural education scenarios to user-centered design simulations and immersive architectural modeling interfaces, frameworks and interface design approaches continue to be explored (Achten, 2000; Bruder et al., 2009; Bullinger et al., 2010; Mobach, 2008). However, few recent investigations have been conducted within the actual realm of architectural practice regarding the potential applications of IVR technology. Through a series of interviews and focus groups, we aim to address this gap by investigating how contemporary architectural practices can use an IVR representation within a project workflow, and the system requirements of an IVR representation interface that supports these uses.

2.1. Representing Architectural Design

2.1.1. Design Cognition and Representation

Within the many disciplines that involve design, several cognitive dimensions are believed to be common amongst any design activity. Of these core concepts, the most important in architectural design relates to the notion of design as a problem-solving activity and the essential nature of a design representation for resolving problems (Visser, 2006). These problems tend to have multiple satisfactory solutions, as they are often complex, interdependent, and lack objective evaluation criteria (Visser, 2009). As designers proceed towards a final design, opportunistic cognitive shifts are applied according to different types of problems encountered during the design process. For example, a designer may first use a top-down approach in order to assess the larger conceptual structure of the design requirements, then shift to a bottom-up approach as they search for solutions, followed by a shift back towards a top-down approach and restructure their approach based on knowledge gained from their search for solutions, and so on (Visser, 2009). However, as designers shift their approach between more abstract to more specific, representations remain essential as the external symbolic repositories necessary for the contextual assessment of both problems and solutions (Goldschmidt & Porter, 2004; Yaneva, 2005).

Beyond the spectrum between abstraction and specificity, representations can also vary in how transient or durable they are. Examples of transient representations include digital models created using a computer, which often do not capture a record of the design process. Drawings and physical models are more durable and provide a more detailed account of the design process. Representations can also be classified as internal or external, with internal representations existing within the mind of the designer, while external representations exist outside and can be shared and communicated between designers. Lastly, some representations can be considered “ready-made”, while most others are “self-generated” by the designer. Such “ready-made” representations already exist and are used for reference or to inspire during the design process. “Self-generated” representations, on the other hand, refer to representations created by the designer during the design process (Goldschmidt & Porter, 2004).

The cognitive processes inherent to design activities depend on the defining characteristics of the representation. As different representations afford the designer different understandings of the project, the choice of representation must be chosen carefully. For example, spatial relationships and conflicts can be discovered using a two dimensional section drawing that would not be apparent in a unified three-dimensional model, and vice versa (Visser, 2006). This degree of abstraction can affect design exploration by reducing or increasing the noticeable features and content of the representation (Yaneva, 2005). By transitioning between a number of different representations during the design process, a designer can gain a greater understanding of the project, thus improving design outcomes (Goldschmidt & Porter, 2004).

2.1.2. Architectural Practice and Representation

More and more, 3D digital models are increasingly becoming a cornerstone representation in architectural practice, and the majority of design development occurs through a digital interface. Beyond merely 3D modeling, BIM tools have revolutionized the field of architecture by offering designers a data rich three-dimensional representation of a project. Newer BIM tools provide parametric design capabilities, allowing dependencies and associations between elements to quickly propagate changes in the model. Models of material finishes, manufactured architectural components, and interior furnishings are often available, granting the power to quickly create a fully detailed representation of the project. Additionally, BIM tools provide a streamlined project workflow through a project by generating perspective renderings, detailed construction documents, and building systems and environmental conditions simulations (Boon, 2009; Eastman et al., 2011). In many ways, BIM tools combine a number of representation possibilities in within a single package. For example, transitioning between plan to section, to elevation, to perspective is a relatively simple operation in most BIM interfaces.

However, the major changes that BIM tools present introduce a number of challenges for architectural practices that plan to adopt them. As with older CAD systems, a complex digital interface inevitably mediates design changes, requiring the user to learn the system and translate their thoughts into the commands provided. This disconnection has been found to result in associative thinking deficits and “tool bias” (Pressman, 2006). Beyond simple interaction with the system, adoption of BIM tools requires firms to allow for more time during the design development phase at the beginning of a project, commonly referred to as “front-loading” (Dowhower, 2010). Although still an immature component of BIM, collaborative design functionality is increasingly included, allowing multiple designers to collaborate on the same project (Abdelmohsen, 2012). However, such features are often still inferior to physical presence and interaction between designers and/or stakeholders. Simultaneous collaboration on the same file also can prove to be an issue with many BIM tools. These issues, as well as a resistance to change found among a firm’s staff have slowed the adoption of BIM in many practices (Arayici et al., 2011). Still, BIM is commonplace in many practices, and continues to increase (Gu & London, 2010).

2.1.3. Immersive Virtual Reality and Representation

With the increasing prevalence of three-dimensional digital representations in architectural practice, interest in viewing and interacting with these digital models through an IVR interface has been growing. In particular, architects seem to be interested in using IVR to develop and evaluate their ideas, and also see potential usefulness in situations where communication with those untrained in reading traditional representations, such as clients or the public, is a challenge. Granting a user an experience in which they could move through a design much as they would in the real world could be a tremendously attractive, persuasive, and informative approach to developing and communicating design ideas.

Still, the details of how an IVR interface should be designed must be answered. What tasks and capabilities should it support, and how? What considerations and requirements should the interface be based on? What should the actual implementation and components of an IVR representation interface look like? To help answer these questions, we must first refer to previous research on general IVR usability issues, as well as previous investigations into prototyping IVR representation interfaces.

Usability Issues in Immersive Virtual Reality

In terms of IVR usability research in architectural scenarios, comparisons between real environments, walkthroughs viewed on a monitor, and IVR walkthroughs viewed through a position-tracked head mounted display reveal issues with spatial perception distortion (Henry & Furness, 1993). Such distance and size underestimation errors have been observed in a number of studies, though recent research involving a connected transition from the real world into IVR can reduce these errors to more tolerable levels (Steinicke et al., 2009). However, because alternative forms of representation often distort or obscure distance perception of an architectural design, an IVR representation of the space stands as a closer approximation to the final product (Henry & Furness, 1993; Riva et al., 2007; van Dam et al., 2002).

Other unresolved issues in IVR technology include the potential for motion sickness (Sharples et al., 2008) and the navigation and orientation errors that occur more frequently when users must rely on only visual motion cues when moving through an environment (Arthur et al., 1993; Klatzky et al., 1998; Wan et al., 2009). Some researchers have proposed that providing supplemental sensory cues, e.g. vestibular and proprioceptive cues, might help to compensate for the differences between real world navigation and orientation with users in IVR (Riecke, 2010).

Though specific usability challenges are still being explored, few debate IVR's capability to grant an experience of a space. Indeed, how the space might "feel" is likely best conveyed through an IVR interface that is natural and intuitive. This "feeling" is experienced when the user experiences a psychological sense of being in the VE, a phenomenon known as *presence* (Schubert et al., 2009.; Slater & Wilbur, 1997). For our exploration of architectural IVR representations, this can be broken down into *spatial presence*, the psychological experience of being physically in the environment (Schubert et al., 2009), and *social presence,* the psychological experience of being in the presence of others (Heeter, 1992). Before a user can feel presence, however, the technology must facilitate *immersion*, referring to the extent to which the interface engages the user

(Lombard & Ditton, 1997). While there are different types of immersion, we will focus only on *sensory immersion*, which refers to the qualities of a VR interface that immerse the user via sensory input. Other types of immersion rely on challenging the user (challenge based immersion) or engaging the user's imagination through story (imaginative immersion), both of which are outside the scope of this thesis (Ermi & Mäyrä, 2005; Schuemie et al., 2001)

Previous Research on IVR Architectural Representation Interfaces

Given the potential that IVR offers as an architectural design representation, a number of researchers have developed interface prototypes of IVR architectural design tools. Of these prototypes, approaches tend to be oriented around either immersive modeling applications, occupant testing scenarios, or simple walkthroughs of the space. Unfortunately, these tend to be mere proof-of-concept works and design decisions are not informed by any formal investigation into existing practice, and few are evaluated in terms of usability. Below, we outline three notable explorations on the application of virtual reality in architectural design scenarios.

In an effort to create a more sketch like modeling tool for architects and other design professions, Achten et. al. (2000) designed and evaluated a pointer based modeling tool for basic 3D sketching during initial phases of design. Several focus points were outlined to guide the design of the system, with a simple user interface, easy creation and manipulation of content, and easy navigation in the VR environment being of primary importance. The majority of their research focused on the specific technical components and features of a more natural modeling interface, with switches between interaction modes being of primary concern. At the highest level of the interface, drawing and navigation modes allowed users to switch between simple voxel based modeling actions (sketch, curve, delete, orientate, and move) and locomotion actions through the VE (walk, fly, rotate, and top). The final prototype was given to and informally evaluated by Wiegerinck Architecten Arnhem, an architectural design firm. While their response was generally positive, requests for additional features in both terms of both modeling and navigation were made.

Although not an IVR interface, this exploration confirms that practicing architects find potential in a more natural sketch modeling interface. One of the major limitations of the system lies in the inability to model and navigate simultaneously, making it difficult to model while moving through the space. Furthermore, the lack of detail in describing responses from practicing architects limits what can be gleaned from this study. However, to the best of our knowledge this example stands as the natural sketch modeling interface evaluated in practice (Achten, 2000).

Bullinger et al. (2010) investigated the potential of a user-centred design approach within the architectural design process. Their research focused on the creation of a design process framework, implementation of the framework in a real world setting, and finally, an assessment of the framework and associated technology. Their evaluation framework included usability engineering methods and participatory design evaluations of the designed environment prior to construction. Using qualitative methodology, a case study investigated the implementation of this model for the construction of the Fraunhofer IAO Centre for Virtual Engineering Building in Stuttgart Vaihingen, Germany. Shortcomings were found in the translation of the existing engineering interaction tools to architectural design, but overall, their findings supported the usefulness of such a process. Users found the approach to be beneficial and informative, though technological limitations impaired the technique at various points of the process.

Their research, although focused on a process-oriented participatory design framework, supports the idea that virtual reality can provide a more realistic and informative experience of the design. Limitations and open issues of the study describe areas that should be carefully considered for the design of a similar system. Specifically, they encountered problems in user learning of the system, implying that interface control must require a lower learning curve. Furthermore, their attempt to implement a complete system may have been overly ambitious as a first step (Bullinger et al., 2010).

A different approach was taken by Mobach, in which he looked specifically at the use of virtual reality in architectural design using participatory design evaluation techniques. His research investigated the use of virtual reality user group evaluation for the design of a pharmacy using a virtual theatre at the University of Gronignen in the Netherlands. Using a mainly quantitative methodology, the research was conducted through a series of questionnaires administered at various points during the design session. The paradigm was pragmatic, as qualitative data on design changes and group behaviors were also provided using a case-study method. The design sessions yielded significant changes from the existing pharmacy layout and structure, and the resulting construction was evaluated using questionnaire feedback from the staff and customers. The redesigned pharmacy was rated significantly higher on user satisfaction measures, and the author concludes that a user group evaluation method involving virtual reality improves the resulting design dramatically.

Their research offers a useful framework for evaluating architectural design using a focus group, though much of the study's value lies in its confirmation of virtual reality guided design decisions. His findings on design quality improvements and customer satisfaction support the notion that virtual reality techniques can improve architectural design outcomes through enhanced review capabilities (Mobach, 2008).

2.1.4. Research Goals and Approach

Given the importance of representations in architectural design, the potential usefulness of an IVR representation interface, and the increasing accessibility of high quality IVR technology, interest in the development of an IVR interface for architectural practice is expanding. However, the question remains unanswered regarding where and when the interface can be useful, and how the interface should be designed to respond to these uses. Previous research does offer general usability considerations for virtual reality interface design, but to the best of our knowledge there exists no research that explores the spectrum of potential usage scenarios and requirements for an IVR interface for architectural practice. Consequently, our main research goal was to fill this gap by speaking with professionals in the realm of architecture to uncover potential usage scenarios and outline the requirements of an interface that responds to the needs of each scenario. By presenting scenarios and exploring the requirements of an architectural IVR representation interface, our main research goal was to inform the future development of an IVR interface that fully capitalizes on the benefits that IVR can offer to designers, clients, and everyone that relies on the built environment.

To help answer this overarching research goal, we also sought to understand the roles that current representations play in the design process and how these could be supplemented or replaced by IVR representations in different usage scenarios. Beyond this, we explored system requirements of IVR representation tools and how these could work within a BIM or 3D modeling design process. Because not all practices have adopted BIM technology or develop 3D models, we also sought to understand how the type of practice affects design representation choices and project structuring.

Given these goals, we divided our research into two sub-phases. The first sub-phase consisted of one on one interviews with local Vancouver architects. These interviews focused on understanding the role of design representations in contemporary architectural practice, how design representations are used in different types of practices, and how IVR representations could be useful in the architectural practice.

During the second sub-phase we conducted focus groups with staff from the Vancouver office of the architectural design firm of Perkins + Will. Each session involved group discussions exploring current practices, instances where IVR might be useful in their practice, as well as creative conversations on what the system requirements of an IVR system should be.

2.2. Methods

To pursue our research goals and explore the research questions outlined in Chapter 1, we first conducted semi-structured interviews with local Vancouver architects. Following this, we organized and ran two focus groups within the architectural design firm of Perkins + Will in Vancouver, with one of the focus groups involving junior staff, and the other involving senior staff. All participants were volunteers found using a purposive, convenience sampling method.

2.2.1. Interviews

Seven participants were recruited from architectural practices in and around Vancouver, British Columbia for an semi-structured interview lasting about an hour each. Participants were found via word-of-mouth, and were required to have worked long enough and recently enough to be acquainted with the challenges faced in contemporary practice, and were also selected so as to represent a range of perspectives on architectural practice. Each participant had at least 4 years of experience working in an architecture firm, not more than 4 years previous to the interview. Each interview was conducted at their place of work or in a quiet setting, and audio recordings were taken for later analyses.

Each interview consisted of two parts: a seated interview and a tour of the office and their design representations. Following documentation of informed consent, participants were asked to give their name, title, and background. After this general introduction, broad questions were asked in an effort to prime participant's imaginations towards the future of practice (e.g., "Describe what design tool technologies you imagine architects will be using in 20 years?").

Questions regarding the temporal and organizational structure of projects were asked next in order to understand how IVR representations could be used during the process and presentation of a project in relation to this organizational structure and the individuals involved (e.g., "How are your current/recent projects organized in time, internal personnel, and external personnel?").

This was followed by questions oriented around the current use of representations during the design process in an effort to understand how process representations are currently used, for what purposes, and how an IVR representation might replace or augment these representations (e.g., "What path does the design process take in your practice?"; "How do you assess how the designed space will be experienced, or feel?").

Questions about client presentations were asked after this in order to understand how presentation representations are currently used and how an IVR representation might solve issues or improve client responses (e.g., “How do clients respond to your or your team’s design representations during review sessions?”).

We then presented a short demo of a stereoscopic HMD (Oculus Rift DK1). To end the seated portion of the interview, participants were asked a series of questions regarding IVR technology in architectural practice to gather feedback on how they imagine IVR could be used in their work (e.g., “In the future, do you think an immersive HMD experience could be useful in your design process?”; “Do you think this technology would be useful in client presentation situations?”).

Participants were then asked for a short tour of their working environment, with specific focus on examples of their design representations. Observations of their working space allowed us to see what and how representations were being used, as well as how an IVR representation interface might fit into their working environment. Following the interview, participants were thanked and offered a coffee as compensation (refer to Appendix A.2 for the full interview questions outline).

2.2.2. Focus Groups

Following the interviews, two focus groups were conducted by two researchers at the offices of Perkins + Will in Vancouver, BC. In order to ensure that participants would not feel at all inhibited in responding to questions or discussing their ideas, the first group was made up of senior staff with six participants and the second of junior staff with five participants. Focus group participants were recruited on a voluntary basis through a contact at Perkins + Will, with an attempt to include as broad of range of participant backgrounds as possible within each group. Each session was approximately two hours in length, and video recordings were taken for later analysis.

Each focus group began with each participant’s written affirmation of informed consent, followed by a brief description of the structure of the session. After this, the group was presented with two discussion questions relating to the typical design processes at the firm, and the advantages and disadvantages of the digital design tools used in recent projects (“Can you outline a typical design process you use for your projects?” and “Can you talk a bit about the pros and cons of the computer aided design tools you use?”).

A very brief introduction to IVR technology came next, with another two discussion questions after this (“Imagine you are working on your current project. How would you use a more immersive virtual reality workstation in your design process?” and “What are the most promising tasks/scenarios such a system?”). These questions were oriented towards how an IVR system might be used in their firm’s design processes, and which design tasks would benefit the most from the use of an IVR representation tool.

After these discussions, the junior level group (the senior level group was unable to complete the brainstorming session due to time constraints) participated in a brainstorming activity known as “brainsketching” (Vidyarthi, 2014). Given a sketchpad and pencil, participants were asked to sketch their ideas of what their dream IVR interface would look like and what features it would have. After a short time, the paper would be passed to the person on the left, and the sketching would continue. This was repeated until everyone had worked on all the sketches, and was then followed by a group discussion of the drawings. Once this was complete, a prototype IVR locomotion interface was shown to the participants, and a short requirements questionnaire was completed individually and then discussed as a group. This questionnaire presented a list of potential system requirements (e.g., “The interface should have a 3D display”; “The interface should allow hands free locomotion”) with a rating scale assessing importance between 1 and 10 for each requirement. (See Appendix B.3 for the complete requirements questionnaire)

Lastly, participants completed another brainsketching activity that included the aforementioned IVR locomotion interface. After the focus groups, participants were thanked and encouraged to ask any questions they had about the study. (refer to Appendix B.1 for the full focus group outline).

2.2.3. Analysis

We transcribed and assessed audio recordings for the interviews and video recordings of the focus groups according to our main goal of finding potential usage scenarios and system requirements. One researcher analyzed the interviews and focus groups, and each scenario mentioned by participants was recorded and specific information regarding requirements was noted. This researcher was familiar with contemporary topics in IVR and referenced this background knowledge to inform the gathering of the requirements of the system. With these notes on scenarios and requirements, the researcher then constructed a list of each.

Specifically for the focus groups, the results of the brainsketching exercises and requirements questionnaire were discussed as a group after completion. During transcription, information on requirements that arose from these discussions was added to the notes for each scenario.

2.2.4. Validity and Reliability

We devised our own set of questions for both the interviews and focus groups, as we found no previously published question set that inquired about usage scenarios and system requirements for an architectural IVR system. Because ours is the only study to use the set of questions we composed, we cannot assess inter-study reliability. We found that the questions successfully addressed the intended content and goals of the study, so they were not revised during the course of the interviews and focus groups.

During our investigation we sought out a range of potential users from the realm of architectural practice in an effort to improve the external validity of our findings. This idea of selecting a sample that grants the widest understanding of a phenomenon is advised by Merriam et. al. (2002). Also, according to Arayici et. al. (2011) our approach of consulting both higher and lower level users on the use and adoption of new architectural design technologies would be more productive than presenting a solution without their involvement.

One researcher analyzed the results of the interviews and focus groups. Given that our conclusions regarding usage scenarios and system requirements were informally clarified with participants during interview and focus group discussions, we concluded that interrater reliability measures were unnecessary.

2.3. Results and Discussion

The idea of augmenting the contemporary palette of design representations with IVR technology proved to be a topic of great interest and excitement for those that we spoke with. Contemporary design representations were found to be lacking in a number of areas, particularly concerning instances where intuitive interaction, an immersive experience, scale assessment, stakeholder persuasion, and design communicability were important factors.

In order to gain a more complete understanding of the potential usage scenarios and the associated system requirements of each, both interviews and focus groups were conducted. The interviews allowed participants to provide their private opinions and responses to questions about current architectural practice, how IVR representations might be useful in practice, and potential usage scenarios for an IVR design representation interface. This method of interaction with participants allowed the interviewer to explore an individual's perspectives and ideas more thoroughly than with the focus groups, given the one on one nature of the interaction. Not surprisingly, we saw that specific IVR usage scenarios and requirements were focused upon different professional backgrounds and organizational positions. Although not formally confirmed, we generally found that interviewees at higher levels within a practice focused more on usage scenarios associated with presentation of a project to clients, while more junior staff involved in everyday design tasks, such as visualization or detailing, focused more on scenarios associated with the design process.

In contrast with the interviews, the focus groups were more conversational and ideas tended to build on one another as the participants talked about each discussion question, which in turn resulted in a more creative and involved exploration of ideas. Just as with the interviews, the focus groups explored contemporary architectural practice, how IVR representations might be useful in practice, and potential usage scenarios for an IVR design representation interface. However, the focus groups included brainsketching and requirements questionnaire activities, which allowed more focus on exploring and informing the system requirements of different scenarios. Between the junior level and senior level focus groups, we again informally observed general differences in the focus of discussions, with the senior level staff generally centering discussions more on client presentation scenarios and requirements than the junior level staff, which seemed to focus more on everyday design process scenarios and requirements. However, these differences were not formally confirmed, and are general observations by those who conducted the focus groups.

2.3.1. Usage Scenarios

During both the focus groups and interviews, participants described a number of specific scenarios in which IVR would be useful. These are described below. Please note that Senior Focus Group Participant 1 and Interview Participant 4, Senior Focus Group Participant 2 and Interview Participant 3, and Junior Focus Group Participant 2 and Interview Participant 2 participated in both the interviews and the focus groups and are the same individuals, respectively.

Immersive Modeling Tools

All of the architects we spoke with who use BIM tools like Autodesk Revit expressed frustration with current BIM modeling interfaces. One of the major difficulties with many BIM tools is that complex geometry is inherently difficult to model. These tools require the user to learn the interface to create such forms, and translating thoughts into form becomes an arduous process. Especially for the initial phases of a project, designers expressed interest in quick and intuitive modeling tools for fast assessment of ideas. According to one of the participants we spoke with, such a natural user interface should match real interactions whenever possible, so as to facilitate the fast creation of what the designer imagines. As described by this interview participant, an IVR sketching environment would be an ideal application for use in their process:

> Interview Participant 3: *“Well in a process like I describe I think it would be amazing, because I've always kind of been fascinated with this idea of being able to… design a building from this perspective… like literally being able to craft it, at one to one. So you can kind of move around the building with this perspective, and be designing it, because I do wonder if you would actually create a different building... or see it in a different way.”*

As a potential extension of this idea, the use of stereoscopic 3D was of interest to one of the participants in particular. He reasoned that because two-dimensional screens are the means by which most architects work currently, much time can be wasted attempting to select an object in a 3D view. He then went on to describe a problem he has faced with modeling, and the potential that a stereoscopic immersive design system might offer:

> Interview Participant 6: *"I think that the perception of depth could be… you know, we get used to what we use, so we're not… and I think it's good in a lot of ways that we get used to it, because otherwise we'd be complaining about our work process on a daily basis. So someone gets used to the limitations of working with a 2D screen knowing that you could have better. The lines on the 2D screen don't differentiate themselves from one another. But you get used to that, you get used to having to… squint your eyes and try to select the right line. But if we ignore that for a moment, the fact that you could use perspective to your advantage so that you move your point of view to be close to this column. And you want to start manipulating the column, but you don't want to lose the context of what's maybe 20 feet away. You don't want to vanish that. So depth would be very useful there. If you could somehow blur, give some sort of indication and maybe the 3D, the steroscopicity of it would help you to distinguish that this is in the foreground. Then with my finger I select one edge of the column and it's not selecting the corner of the wall that's 20 feet beyond. That would improve my workflow, because it's intentional."*

Virtual Site Visit

Increasingly, architects find themselves working on projects many miles away, sometimes never actually seeing and experiencing the actual site they design for. The architects we spoke with agree that this is problematic, as many ideas and realizations come about when visiting the site. During our senior level focus group one participant spoke about the importance of visiting the site and that there are times when it is feasible for only one team member to do so:

Senior Focus Group Participant 1: *"There's a lot of things that you only comprehend when you are in the space and feeling it, rather than seeing photographs of it. I think that for most of our international projects at least one person from the team will be going to see and feel that. So at least there's that. We're trying to download some information [through them]."*

However, while IVR can offer a measure of experiencing a site that an architect might never have, it currently cannot fully replace a fully experienced site visit:

Senior Focus Group Participant 4: *"An interesting example last week: I was in Nanaimo for kind of a pre-kick-off meeting for a project we're going to do there. It's on a sloping site, and the topography's crazy, strange. But one thing I was confronted with was a meeting room that was kind of stuffy, so I opened the windows and there was a wonderful breeze coming off the ocean that came up the hillside and is drawn into the building. That made a little light bulb goes off in my head, saying you know, what's the natural potential for this place? So it's something I wouldn't have known looking in Google Earth."*

Scale Assessment

Many architects informed us about the difficulties in accurately understanding the experience of distance and scale during the design process, and they are sometimes surprised by how the built space feels compared to expectations. Even in scale changes between 3D physical models, surprises and realizations often occur with each shift (Yaneva, 2005). At times, full scale physical mock ups will be used to better understand issues of scale.

Junior Focus Group Participant 2: *"When we did that simple cardboard section cut-out and put it in the atrium. As much as you think you understand scale, when you get refreshers like that, you're like wow, this is big. You know it's tall, but..."*

Even though these are often rough in terms of detail, they can still be costly and time consuming to assemble. An IVR representation on the other hand, while still not a perfect representation, can offer a much better idea of scale than other representations, and may cost less than assembling a full scale physical mock-up.

Design Annotation

Design representations are grounded in the act of embedding information in an abstracted form. At times this information could be spatial or material, while other times it can be textual or technical. Currently, most annotation is done using 2D representations, which can be more complicated to use and can obscure forms that exist in 3D space. Interactive IVR environments could provide a more realistic form of representation that allows expression of a spatial environment while permitting the embedding of other information or comments in the 3D space. Referencing this idea, one of the senior focus group participants had this to say about supporting commenting as he compared design review and immersive modeling approaches for an IVR interface:

> Senior Focus Group Participant 5: *"So the design group is more, probably reviewing and commenting, rather than the designer is actually being able to manipulate things while you're in that [setting]."*

Conflict Detection Tasks

During the design phase, architects and engineers attempt to find any potential conflicts or errors with the design prior to actual construction. To avoid costly these on site modifications and mistakes, design representations are used to assist inspections and discussions. However, the level of abstraction of these representations can prevent conflicts from being detected. According to some of the architects we spoke with, a more realistic and immersive representation could help reduce the number and frequency of these errors before construction begins:

> Junior Focus Group Participant 3: *"It might be good to actually take a contractor through what the completed project is going to look like. I know that sometimes really simple things [referring to errors] don't get picked up just because, I don't know, they're not looking at the drawing or you just had a photo to send them, and they were like okay, that's what it's supposed to look like here in the drawings. Then it would have worked."*

Design Review

Design representations serve as the cornerstone for design communication, and when attempting to convince others of design ideas the choice of representation can dramatically affect how persuasive or communicative the ideas are. In cases where 3D and experiential components need to be conveyed, IVR representations could be extremely helpful for facilitating group discussions.

> Senior Focus Group Participant 1*: "… there are two different lines here that could occur, and maybe there's more. One would be during the design review, where basically the team has already designed the project to a certain phase, and there is the time where reviewers come in to see the project at this phase and sort of provide comments and the direction for the future. So it might be a good way at this time to have the reviewers immerse themselves into a building and see it from a different perspective, and maybe be able to see a better way that would enhance or would make the type of feedback you can get better, because you get to absorb more of the design… so you can give more feedback."*

Precedent Observation

Referring to previous works is common in the field of architectural design. This may include gaining inspiration by exploring other's work, or presenting precedent design ideas to others and possibly borrowing those ideas for inclusion in a new project. For the latter, the client is sometimes shown these precedents to communicate what the designers would like to do with the project at hand. Often times, physically accessing the space is not possible, so photos, plans, and other basic representations are used to convey these ideas.

> Interview Participant 6: *"…if you're looking at precedents of what's been done in the past throughout the world that are related to the design condition that you're trying to solve. And you look at precedents, and often you only have the information that's available to you in a few photos that you've searched online, and maybe there's a short article; a two page article that describes some of what's on the photo. In some cases you might not even have the time to read through all of it. So you're looking at precedents and you're in a group setting*

discussing what's been done, thinking about what you're trying to solve. The information that you have is very ambiguous; the photograph could be misleading. You could be drawing conclusions that are completely erroneous, but you don't have time to validate; you don't have time to verify exactly what's happening in those precedents."

Furthermore, precedent representations that use IVR can help others to experience the space in ways that other representations are incapable of, potentially increasing how persuasive a designer can be when communicating project ideas.

3D Data Visualization

Within a number of different practices, the role of computational design and BIM seems to be expanding, particularly for larger firms. These tools are increasingly providing simulations of complex spatialized data that can help inform design decisions. The resulting visualizations can be better explored using immersive stereoscopic displays (Pressman, 2006; Ware & Frank, 1996). One of our interviewees specializes in creating these data representations, and he described the challenges with exploring, understanding, and communicating this information to others:

Interview Participant 6: *"Most of my representations are fairly schematic. I never get into anything close to realistic representations. My representations are usually in 3D, and are often representing data. …if you start going crazy with colours and numbers, it will become very difficult to read. So usually when you're representing that way it has to be fairly simple. So it would be, you know, a colour coding system, or the gradient of colours represents something that's meaningful to the team at that particular time. So if they're concerned about the length of window units. I can colour code all of the window units so they can focus their attention on an area of the geometry of the project… where the size of the windows has crossed a threshold that they should be aware of. That might be a big issues for one reason or another. Numbers to lay out numbers along the building. Similar to when you're showing radiation levels within the space, and you have a number map spread across all the surfaces of the interior. That kind of a display of information is also common."*

Isovist Viewing

Understanding the relationship between a location in the design and the views one might have is a common task during the design process. An interactive IVR representation of the design can provide a user with such views and the user can assess the design in a way that mimics the act of looking around the space. In response to the interviewer mentioning the idea of an immersive isovist, one participant responded enthusiastically:

> Interview Participant 2: *“Definitely, our New York office actually did a representation for a client where you would click on certain points, and he rendered a 3D panorama of that view, for that project. So the client could jump from different hotspots in the project, and then view around and get what it feels like in that certain spot. That was pretty cool. Yeah, something like that, I could definitely see it having potential.”*

Experiential Evaluation

Many of the participants we spoke with were interested in using IVR for an immersive experience of a project prior to construction. Currently, two-dimensional renderings and models are used to convey the experience of a designed space. According to many interviewees, when a space needs to convey a certain feeling to the occupant, the ability to use IVR as a design representation would be far superior for imparting affect.

> Interview Participant 6: *“We want to be able to anticipate, long before construction happens, so that we can start comparing the comparative advantages between one experience and another, and say that: ‘So if we did this, the experience would change in this way, and then compare the relative advantages of these two.”*

Immersive Promotional Simulation

In larger projects, particularly those that require public approval or preconstruction sales, the idea of an immersive promotional simulation has great potential when persuasion and communicating experience are important objectives. Granting someone who is not sure about the project a more realistic experience of the design can help alleviate uncertainty and improve the chances of success.

> Senior Focus Group Participant 2: *“I'm thinking also about outreach possibilities. For example at SFU the client group is actually a significant student base. And they have limited accessibility to understanding what's happening within the design process. Albeit SFU has tried to make it as transparent as possible. They have a great website, visuals are constantly being updated, we host meetings at a singular location at SFU, but attendance still could be better. They're still not getting... So I wonder, if you had something like this, as a station at this location. At the Build SFU site, this would be a great opportunity to [get students thinking:]... “I'm interested in the technology, but I'm also going to get a bit of a building.”*

Future Occupant Testing

Designing an environment that fully responds to and meets the expectations of future occupants can be a challenging task, especially when those that will be using the space have specific needs or the occupant experience could have a dramatic effect on the success of a project (e.g., hospitals, retail, production facilities). Testing users in IVR simulations and gathering their experiences and feedback could help to inform the design and reduce risks that the project will not respond to future occupant needs.

> Senior Focus Group Participant 4: *“I think it depends on the process that you have. Sometimes they're hiring designers to design and lead, and too much input can be a confusing thing to the process, so I think there’s a consultation that’s necessary, but it’s what you do with that consultation. I mean I could see something where you have an exit questionnaire/exit interview when there’s an experience being had, and you can gather the opinion and consider the opinion.”*

Guided Group Presentation

The idea of an IVR guided group presentation held great appeal for many of the architects we spoke with, as it combined the communicatory and persuasive potential of

IVR with the ability to have focused discussions about the design. Furthermore, in the competitive world of architectural practice, the ability to impress and persuade clients can dramatically affect the success of a firm.

> Interview Participant 3: *"…there's no doubt from a client perspective, like how powerful this would be. For them to be able to understand the space that you're creating; I think that would be immensely powerful."*

2.3.2. Scenario Classification

We found that system requirements for any scenario were typically defined by two factors: if the IVR representation is intended for internal process work or external presentation work, and if the scenario involves an individual or multiple users.

Interestingly, the two focus groups also revealed differences in their values for an IVR system, with junior staff generally placing greater importance on system requirements related to individual work, while senior staff generally placed greater importance on system requirements involved in a multiple user system.

Internal Process Scenarios

Internal process scenarios involve IVR representations in which designers, engineers, or construction professionals can observe, change, and review designs without the involvement of clients, stakeholders, or the public. In these situations designers can obtain a deeper understanding of the environment they're designing, work intuitively on 3D sketching and modeling tasks, and avoid costly mistakes by reviewing the project in a natural and intuitive way.

Just as with traditional representations in architectural practice, expectations of quality and refinement for IVR process representations tend to be lower when compared with presentation representations. Movement through the environment should be relatively unrestricted, locomotion interfaces should be moderately easy to learn, and hands should be free to enable communicative gestures and gestural interaction with the virtual environment. Displays providing stereoscopic 3D are preferable, as the extra depth cue can assist with selection tasks and improve environment realism. Most importantly, these environments and systems should be quick to setup and use, and risk of motion sickness should be low. Other system requirements depend on whether the system will be used by a single individual or is intended for multiple users simultaneously.

Individual Users

Single user scenarios can include the application of immersive modeling tools, virtual site visits, scale assessment, design annotation, conflict detection tasks, precedent observation, 3D data visualization, isovist viewing, and experiential evaluations.

For these individually oriented scenarios customization of the interface is desirable, and settings should be saveable for reuse by the user at a later time. Fast transitioning into and out of the interface should be supported, and sensory immersion should be maximized by minimizing unrelated sensations from the outside world (Ermi & Mäyrä, 2005).

Multiple Users

These multi-user scenarios can involve the use of immersive modeling tools, virtual site visits, scale assessment, design annotations, conflict detection tasks, design review, precedent observation, 3D data visualization, isovist viewing, and experiential evaluations.

In scenarios where multiple designers utilize an IVR interface to discuss and coordinate during the design process, communication between individuals should be prioritized by allowing individuals to see and express non-verbal cues like facial expressions, gestures, and body language. Supporting social presence is key here, and with current technological limits, the interface should be partially immersive to assure that non-verbal communication cues aren't obscured (e.g., an HMD covering facial cues). For example, an internal design review with multiple users might have a shared screen or multi-sided projected environment like a CAVE to allow users to see each other while discussing referencing the representation.

External Presentation Scenarios

External presentation scenarios are focused on using IVR representations for the straightforward communication of design concepts and features to clients, stakeholders, future occupants, and the public.

In comparison to process scenarios, presentations using IVR should involve a great deal of finesse and care during their creation. When presenting partially complete models, the presentation should be guided to focus users on the developed portion. Consequently, locomotion interfaces can be fairly restricted for this category, but should have high learnability and ease of use. Stereoscopic 3D displays are preferable to improve environment realism and immersion. The risk of motion sickness should be low, and just as with process scenarios, other system requirements will depend on whether the system will be used by single users or by multiple users.

Individual Users

Single user scenarios could include precedent observation, 3D data visualization, isovist viewing, experiential evaluation, future occupant testing, or immersive promotional presentations.

For these presentation scenarios, the IVR interface should maximize sensory immersivity by minimizing unrelated sensory cues from the outside world. For future occupant testing scenarios, the system should support collection of relevant behavioral data. Individual promotional presentations directed towards acquiring occupants or persuading the public should focus on a highly immersive simulations that minimize motion sickness and provide a locomotion interface that is easy to understand and learn.

Multiple Users

These multi-user scenarios can include precedent observation, 3D data visualization, isovist viewing, experiential evaluation, future occupant testing, or guided group presentations.

In multiple user presentation scenarios, interfaces should focus on maximizing communicative potential between users and supporting non-verbal cues like facial expressions, gestures, and body language. For this type of scenario the focus of the interface should be on providing partial sensory immersion and facilitating social presence, while also facilitating personal and environmental presence.

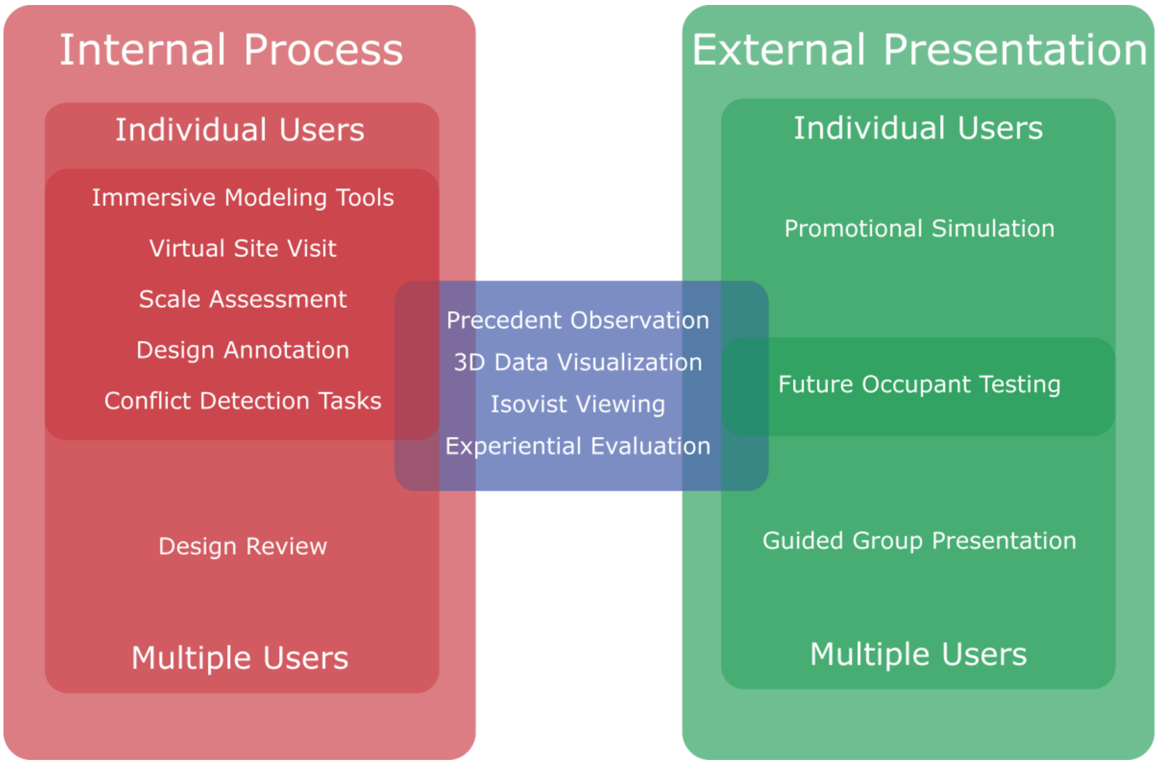


Figure 2.1. Scenario Classifications

Note. In the diagram above, we summarize where each scenario falls according to the two dimensions: Internal vs External & Individual vs Multiple

2.3.3. System Requirements

Following from our scenario classifications, we sought to outline the system requirements for an IVR interface that either supports, or could be expanded to support, each scenario. As such, the scope of these requirements includes the basic system requirements our scenarios have in common, and does not include more specific requirements related to certain scenarios (e. g., gestural support for immersive modeling or voice recognition for design annotation). Below we list the three necessary components of an IVR system for architectural practice and outline the basic requirements for an IVR interface that can support each of the scenarios. We base these on feedback from our focus groups and interviews, as well as previous research on virtual reality interfaces. Broadly speaking, these requirements refer to the capabilities of an interface and how the interface should work. More specifically these refer to what the interface provides the user, as well as constraints, goals, and targets (Wiegers & Beatty, 2013).

Visual Display

When it comes to understanding and experiencing an inhabitable space, vision is arguably our most important sense. On a practical level, the majority of a building's future inhabitants will use their visual system to operate within the space, and on a more basic level spatial tasks such as distance perception, motion perception, and navigation and orientation are strongly influenced by visual stimuli (Arthur et al., 1993; Harris et al., 2002). However, the type of visual display can greatly change how users interact with an IVR representation interface. For example, an HMD, while facilitating high sensory immersion (Ermi & Mäyrä, 2005), may inhibit eye contact and other social cues between users, which was an important multi-user system requirement found in our interview and focus group exploration of practice.

To assist with the selection of a visual display, we outlined a list of requirements that should be considered in the design of an IVR representation interface based on our findings from our focus groups and interviews, as well as relevant literature.

Facilitate Sensory Immersion

The feeling of being present within the space is the key benefit of IVR, as no other design representation provides that experience. Visual stimuli can have a strong influence on a user's feeling of immersion within the virtual space (Bowman & McMahan, 2007; Slater & Wilbur, 1997). The architects we spoke with indicated that the experience of sensations and the ability to gauge the resulting "feeling" in the space (e.g. seeing that a red wall does not feel overwhelming, hearing that sounds in a space are calming, etc) would be a key benefit of an IVR architectural design representation. Consequently, providing the user with immersive visual cues is an important requirement. However, in some instances increasing sensory immersion may conflict with the need for social interaction (see below), in which cases at least partial immersion is necessary. For example, in multiple user scenarios the goal is to have a joint immersive experience where users can communicate and discuss the design. In these scenarios visual displays that inhibit non-verbal communication between users (e.g. HMD, etc.) should be avoided.

Allow Social Interaction

According to our conversations with architects, a large part of the actual designing requires communicating with others about the current state of the project. Social interaction consists of more than just verbal communication, with eye contact, facial expressions, and body language conveying large amounts of information. For example, the architects we spoke with during our senior level focus group mentioned this in terms of a client presentation, where seeing their responses is very important for understanding their needs. Furthermore, sharing a view with others allows individuals to discuss and reference a design representation, which can significantly enrich the interaction. Given this, the choice of visual display should reflect the need for users to communicate when multiple users are involved.

Minimize Motion Sickness

Motion sickness is one of the key concerns for IVR interfaces, especially with regards to visual displays (Reason, 1978; Sharples et. al, 2008). This is usually the result of sensory conflicts (i.e., sensations do not "sync" and relay conflicting information to the brain). Minimizing these conflicts (e.g., minimizing low frame rates, conflicting vestibular and visual cues) decreases the chances of experiencing motion sickness, which can render an otherwise useful design representation useless.

Maximize Affordability

While other design and engineering disciplines (e.g., automotive and aeronautical industries) have been using IVR for decades, the high cost of interfaces in the past has been a contributing factor to the lack of adoption within architectural practice. Our conversations with architects in both interviews and focus groups confirm this. For the usefulness of IVR to be explored, architects need to adopt the technology on a large scale, meaning that the cost the interface should be low. Consequently, our requirements recommend a consumer level visual display for an IVR representation interface. Still, the affordability of a visual display can vary greatly, and should be carefully balanced based on a firm's budget.

Maximize Ease of Setup

Based on responses from the architects we spoke with, simplicity and ease of set up were common desires for the scenarios we found, with a number of participants desiring a fairly simple and fast transition from the previous task into an IVR representation interface. More specifically, the time required begin using the visual display after initial set up should not be more than a few minutes, and ideally the physical interface should be ready to use immediately.

Locomotion Interface

Beyond providing a visual display, providing user locomotion is another important component of an IVR representation. With a locomotion interface, a user gains control over movement through the virtual environment, and it ideally should give the user the convincing natural and embodied impression that they are moving through the VE in order to engage our brain's spatial perception systems and facilitate sensory immersion (D. Bowman et. al., 1998; Riecke, 2010). This experience can be accomplished by initiating self-motion cues via the visual, auditory, vestibular, proprioceptive, and tactile senses (Riecke, 2010), though many other factors influence the quality of a locomotion interface.

Below we describe a number of requirements that are important to the design of a locomotion interface, which are primarily based on requirements gathered from our focus groups, interviews, and relevant literature.

Facilitate Sensory Immersion

Ranging from simply pressing a button to physically walking in a space, the means of locomotion can greatly affect how involved a user feels within the virtual environment. Ideally, we want to provide an embodied locomotion interface so that the user feels enough sensory involvement in the VE to initiate a feeling of spatial presence. By facilitating spatial presence, the user can interact and perceive the space more like they would in the real world, and tap into the brain's spatial perception system. This can help users intuitively navigate and orient themselves in the VE and more accurately experience and understand the space (Bowman & McMahan, 2007; Ermi & Mäyrä, 2005; Slater & Wilbur, 1997).

Maximize Learnability

For the most part, we intuitively understand how locomotion works in the real world. However, unless an IVR locomotion interface uses real world walking for locomotion, we must learn how to operate a locomotion interface that operates using a different set of controls. Based on feedback from the focus groups and interviews in, the locomotion interface should be easy to learn (less than a minute for clients, a few minutes for designers) to accommodate novice users in scenarios where they must use the system without practice beforehand. Other scenarios outlined in our focus groups and interviews allow users time to practice and learn, though even then users should feel fairly comfortable after a few uses. Consequently, in order to support all scenarios, the locomotion system should be fairly high in learnability.

Maximize Controllability

A concept connected to learnability, controllability refers to a user's ability to control the locomotion system once they've learned how to use it. This requirement was also a result of the interviews and focus groups. Once comfortable with the system, users should be able to accurately and precisely move in the direction and at the speed they intend to without much difficulty.

Facilitating User Orientation & Navigation

Humans have a built in spatial updating system that allows us to travel through the real world while maintaining a sense of direction in relation to the world around us and supports our navigation through the environment. This process is called spatial updating, and occurs automatically when we move through the world and update where we are in reference to the locations around us (Klatzky et al., 1998). While some may be better at this than others, spatial updating for everyone is closely tied to information conveyed through our senses (May & Klatzky, 2000; Riecke et. al, 2007; Rieser, 1989).

However, in virtual reality, a longstanding problem users face involves the tendency to quickly become disoriented and lost (Gaunet et. al., 1998; Grant & Magee, 1998). In each of our scenarios this could present a problem, as users should be able to orient and navigate within the virtual environment without serious difficulty. Ideally navigation and orientation error should be similar to performance in the real world. This is particularly true for scenarios involving user testing of wayfinding through an architectural design, as the goal in these scenarios would be to gauge how future occupants would respond to the proposed design.

By providing sufficient sensory cues to users moving through a virtual environment, we may help users to orient themselves and navigate much like they would in the real world (Riecke, 2010). Therefore, the locomotion interface should leverage enough real world locomotion sensory cues to facilitate spatial updating so that orientation and navigation performance is close to the real world. Provision of these cues should be balanced with other requirements, such as cost and set up time.

Minimize Motion Sickness

When sensory mismatches occur, the risk of motion sickness increases (Cobb, Nichols, Ramsey, & Wilson, 1999; Reason, 1978). Because motion sickness can cause a negative reaction to the design if a client is involved or a designer to learn less from the representation, motion sickness should be minimized. Indeed, for all the scenarios we found in focus groups and interviews, the locomotion interface should avoid presenting the user with sensory conflicts. Even seemingly small conflicts can have an effect; for example, motion sickness would likely occur if a user physically walks forward and the visual display shows movement forward more than 50 milliseconds behind the action (Fuchs et al., 2011; Reason, 1978).

Provide Hands Free Locomotion

While most familiar locomotion interfaces, such as arrow buttons or joysticks, are operated by the hands, this can inhibit gestural communication between individuals, and also inhibits the implementation of a more natural pointer based or gestural modeling interface.

Such an IVR modeling and annotation interface was of great interest to the architects we spoke with during our exploration of IVR in architectural practice, with a desire to naturally point to, edit, and annotate geometry being a repeated theme mentioned by participants. This capability could also be useful for communication in teams or with clients. In conjunction with an IVR modeling and annotation tool, our interface should facilitate seamless interactions with movements through the environment through hands free locomotion. This capability allows users greater flexibility and efficiency in terms of switching between locomotion and other interaction modes involved in an IVR modeling and annotation tool. As we previously discussed, the gestural modeling interface described by Achten et. al. (2000) required users to switch between modeling and locomotion modes, limiting a user's ability to move and model simultaneously. With an interface that does not require the use of hands to move in the virtual environment, users can create geometry while a user moves through the environment.

Beyond IVR modeling interfaces, participants from the focus groups discussed the importance of hands free locomotion for multi-user scenarios, where actions such as gesturing and pointing greatly assist with the communication of design ideas.

Maximize Affordability

The locomotion component of the system should be affordable in order to allow for widespread usage in everyday architectural practice. As we described in above, IVR technology has previously been limited to use in industries with large budgets and centralized design facilities (e.g., automotive and aeronautical design and engineering). Keeping costs to a minimum, while still fulfilling other requirements, ensures that practices can both use and afford an IVR representation interface.

Maximize Ease of Setup

The locomotion component should not require an extended amount of time to set up, and transition into. Our conversations in both interviews and focus groups found that architects were concerned with both efficiency and streamlining workflows in order to develop high quality designs quickly and easily.

BIM/3D File Conversion

The ability to import and display a 3D environment from common 3D modeling formats within a 3D game engine is essential for practical reasons. Without this ability, a 3D representation must be built from scratch within a game engine. This task would likely prove too laborious for the majority of usage scenarios.

Ease of Setup

The conversion from a BIM tool or 3D modeling software into a game engine should not require a large amount of effort. Based on informal conversations with architects, for a medium sized project one or two days should be the maximum amount of time spent importing. This conversion may be done manually, although automated software solutions are currently being developed.

2.4. Conclusion

While the built environment is ubiquitous, design quality often falls short - wasting large sums of money on the construction of failed architectural spaces. Given the importance of representations in the creation of successful design projects, IVR could potentially improve the quality of architectural design in a number of ways. We found that architects are interested in exploring its use in a number of architectural practice scenarios. With the decreasing cost and increasing quality of this IVR technology, future architectural design tools may gain greater representational value by providing more immersive experiences, accurate scale assessments, improved persuasive capabilities, and enhanced design communication.

Primarily, IVR design tools should be integrated into a workflow that involves BIM/3D models that can easily be converted into a real-time environment viewer (e.g., a game engine). This is not essential, although building a VE from scratch for a real-time environment viewer would be a laborious process and would likely be too costly to do in most situations in practice. Additionally, the use of an outside real-time environment viewer adds a process step and additional expertise requirements. Beyond BIM/3D model workflow integration, an IVR interface should involve a visual display and locomotion interface support. Previous research on specific usage scenarios has looked mainly at the visual display as the most important component in VR interfaces for architectural practice, and locomotion is generally seen as secondary in importance (Achten, 2000; Bullinger et al., 2010; Mobach, 2008). Locomotion through these prototypes involved either purely visual displays without individual control(Mobach, 2008), or simple controls based on only input via the hands (Achten, 2000; Bullinger et al., 2010). As expressed by our study participants, a more immersive and embodied sensory experience of moving through the space would be much more desirable and engaging, and allow communication through gestures, as well as support for a future addition of a gestural modeling interface. Additionally, physical motion cues may help users with finding their way through the VE, which is an ongoing problem with current VR locomotion interfaces (Klatzky et al., 1998). With both a hands free embodied locomotion interface and an immersive visual display, this representation tool may then be expanded to incorporate all of the scenarios we outlined by addition of other features, such as gestural modeling.

Indeed, an IVR gestural modeling application in architectural practice, though much larger in scope, has been a subject previous research projects, and many advancements have been made towards this end (Achten, 2000; Bullinger et al., 2010; Jota et. al., 2010; Yi et. al., 2009). A number of designers interviewed expressed interest in the idea of a fully three-dimensional modeling tool, in which specification and modifications occur not only in two-dimensional drawings, but in immersive three-dimensional space. Through an intuitive natural user interface, modification and evaluation can occur within the same realm, decreasing the need for users to translate their intentions into the interface and command structure offered by the design tool. This approach can also be part of a BIM design toolkit, though will likely require a commercial enterprise to offer a useful product. Such a design tool offers great potential in comparison with the purely representational approach, though as we found in our study each approach offers great value.

Using both interview and focus group methods, we have outlined a number of potential usage scenarios the architects we spoke with believed could be useful. Following discussions on their uses and the system requirements for each, we found that the scenarios could be classified according to 2 dimensions: if they are intended for internal process work or external presentations, and if they are directed at individual or multiple users. In future work, this information can be used to guide the system requirements of an IVR design tool based on the intended uses while supporting a maximum amount of usage scenarios without sacrificing usability.

Our exploration of architectural practice not only supports the idea that IVR could solve problems currently facing architects, as well as outlines more specific requirements of systems based on the circumstances of use, but also guides the development of a general IVR representation interface that can later be expanded upon to support all the scenarios we found. Our work represents a much different approach than previous research, and the formal outlining of these scenarios and their requirements stands as a significant step forwards towards the development of a useful IVR representation tool for architectural practice. Based on the common scenario requirements from our interviews and focus groups, we found that the core functionality of an IVR representation tool for architectural practice should include a visual display, a locomotion interface, and a process that converts BIM/3D models to a real-time environment viewer. An interface design that provides these three components can then be built upon to include each of the features that architects dream of when they imagine an IVR representation tool. Only when this foundation is established can the dream that is an IVR architectural design representation tool begin to take shape. In the next chapter we describe in detail the continuation of this dream, with the design and evaluation of an IVR representation interface that supports the core requirements of our usage scenarios.

Chapter 3. Design and Evaluation of IVR Interface

3.1. Motivation

Even the most powerful imaginations sometimes have difficulty understanding and assessing the experience of an environment that is not yet real. Communicating that space to others becomes increasingly difficult as complexity increases. In the field of architecture, overcoming this obstacle is a critical concern, and is the reason why representations, such as plans and renderings, are essential for facilitating the design process (Visser, 2010). While contemporary design representations will always be valuable, many architects are expressing great interest in supplementing their palette of representation techniques with Immersive Virtual Reality (IVR). Combined with the decreasing costs and increasing quality of IVR technology, as well as the increasing prevalence of 3D digital models during the design process, use of IVR representations in everyday practice is becoming more and more feasible. However, the questions of how an IVR representation system should be designed are only just beginning to be researched and evaluated.

While there may be great potential in an IVR representation tool, how such a tool should be designed is still being explored. While others have approached a system design that focused on one specific usage scenario, we instead chose to explore the common ground between potential scenarios and focused our system design on creating an encompassing foundation that can be built upon. Based on the scenarios described by the architects we spoke with in Chapter 2, we found two major dimensions that describe the shared system requirements of such an IVR representation interface: if the interface is used within the firm during the design process or if it is used for presentation to those outside the firm, and if the interface is intended for multiple or individual users. By supporting requirements for these dimensions, our IVR representation interface can serve as a flexible foundation that can enable use during each of the potential scenarios.

Our goals for the design of our IVR representation interface were focused on providing architects with an affordable and immersive interface with both a visual display and locomotion component, as well as a means of bringing the interface into the current process by outlining a process for converting BIM/3D models into a real time interactive environment. Of primary importance for the design of our IVR representation interface was locomotion, which based on our interviews and focus groups was found to be an essential component of the interface. For the most part, previous research has not focused on locomotion, and mainly either passive experiences or hand controlled systems have been explored in practice (Achten, 2000; Bullinger et al., 2010; Mobach, 2008).

One of the primary limitations of VR technology currently lies in the navigation and orientation deficits that are observed when users attempt to find their way through VEs. Indeed, the lack of sensory cues needed to facilitate spatial updating, a term which refers to the automatic spatial orientation updating process that occurs when users navigate through the world, seems to be the primary limitation (Klatzky et al., 1998; Riecke, 2010; Rieser, 1989). By providing vestibular and proprioceptive motion cues, a locomotion interface might facilitate the process of spatial updating and prevent users from getting lost, particularly when rotating (Grechkin & Riecke, 2014; Ruddle, 2013). By helping users remain oriented, we can prevent designers or clients from becoming frustrated and having a negative experience, which will improve the usefulness of our IVR interface and grant more favorable outcomes when attempting to communicate or convince others of design ideas.

In the preceding chapter we investigated the theoretical foundations of IVR design representations, explored potential usage scenarios, and classified the scenarios according to the general system requirements. This current chapter extends this knowledge into the design of an IVR interface capable of supporting these usage scenarios, and describes the quantitative evaluation of the interface to assess usability and system requirements.

3.2. Interface Design and Virtual Environment

Based on the requirements we outlined in Chapter 2, we designed an IVR interface to support two visual displays, one more immersive for individual scenarios, and one that allows users to see and communicate with each other while sharing a visual display. Additionally, we designed an embodied locomotion interface based on previous work by Beckhaus et al. (2007).

3.2.1. Visual Display

As we chose the visual display for our IVR representation interface, we sought to balance our requirements to facilitate sensory immersion, allow for social interaction cues (e.g., facial expressions and body language), minimize the risk of motion sickness, maximize affordability, and maximize the ease of setup.

Given the divergent requirements of the individual user and multiple user scenarios, we designed the IVR representation interface to function with both a highly immersive Oculus Rift DK2 HMD and a Benq W1080ST projection screen display (see Figure 3.1). Both implemented stereoscopic 3D for situations where supplemental depth cues are helpful.

Figure 3.1. Benq W1080ST Projector (left) and Oculus Rift DK2 (right)

Because individual users are not focused on social interaction, we chose the HMD as a visual display, as it can facilitate a more immersive sensory experience for users in comparison to the 3D projection screen. For multiple users, the 3D projection screen allows users to share the display and communicate without removing important social interaction cues such as facial expressions and body language. Both maximize affordability, minimize motion sickness, and are easy to set up and use.

3.2.2. Locomotion Interface Prototype

While choosing a design for the locomotion component of our IVR representation interface, we sought to balance our requirements of facilitating sensory immersion, maximizing interface learnability and controllability, facilitating user orientation and navigation, minimizing motion sickness, providing hands free locomotion, maximizing affordability, and maximizing ease of setup.

In the context of IVR, one of the major challenges remains the issue of user orientation and navigation deficits in comparison to the real world. These problems can lead to unhappiness and frustration (Gresty et al., 2003), and in the context of an IVR interface for architectural practice, using such a design representation could cause misunderstandings between designers or clients if misperceived, or cause clients or the public to form a negative opinion of the design. Most researchers agree that the issue lies mainly in a lack of engagement of our brain's spatial updating systems (Klatzky et al., 1998; Rieser, 1989). While visual stimuli are important for spatial updating to occur, research shows that allowing body based cues can assist with spatial updating in VR (Ruddle, 2013). These deficits in orientation and navigation in VR have been shown to be improved by eliciting self-motion cues by offering motion cueing (Harris et al., 2002; May & Klatzky, 2000). Research into low cost leaning interfaces that do not require motion actuators have been shown to improve these deficits, as they support motion cueing upon leaning or rotating to provide vestibular and proprioceptive cues to the user upon their self initiated movements (Beckhaus et al., 2007a; Grechkin & Riecke, 2014; Kruijff et. al, 2015; Marchal et. al., 2011)

Consequently, we sought to provide a locomotion interface that provided motion cueing while remaining portable, safe, affordable, and easy to learn and use. Because no consumer level locomotion interface exists that fulfilled the requirements to our satisfaction, we investigated low cost embodied locomotion prototypes, such as the

“Joyman” by Marchal et al., (2011) and the “ChairIO” design of Beckhaus et. al., (2007). In particular, the Joyman interface found that immersion ratings were improved in comparison to a traditional joystick while using either an HMD or a screen as a visual display. However, the majority participants in their study rated the Joyman to be harder to use than the joystick. The Joyman also relies on the use of hands, which in our case would restrict architects from using their hands for other tasks, such as communicating with their hands or engaging a system with gestural input controls. The ChairIO, on the other hand, does not require the use of hands to control, and general user tests were done in terms of controllability. Overall, findings were positive, and most users were able to learn to use the chair quickly and easily.

Through augmenting a commercially available Swopper chair (see Figure 3.2) with a tracking system, the user can move through a virtual environment by leaning and rotating the body to control their position and orientation in an immersive visual display. While the original ChairIO interface required a prohibitively expensive electromagnetic motion tracking system, we instead used an inexpensive TrackIR 4:PRO tracking system, which costs around $100 USD (see Figure 3.2) to provide a locomotion interface that allows 3 degrees of freedom (DOF) about a central pivot point at the chair’s base. Changes in yaw, pitch, and roll are read via the 3 point reflector mounted to the seat with the infrared light emitter and camera base station on the floor below the reflector (see Figures 3.2, 3.3).

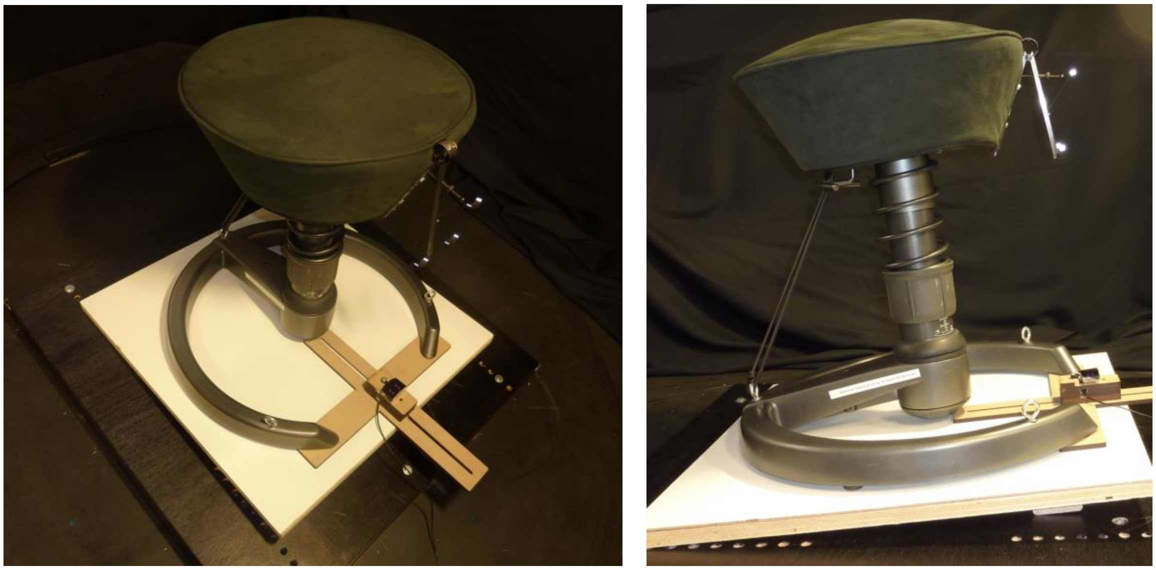
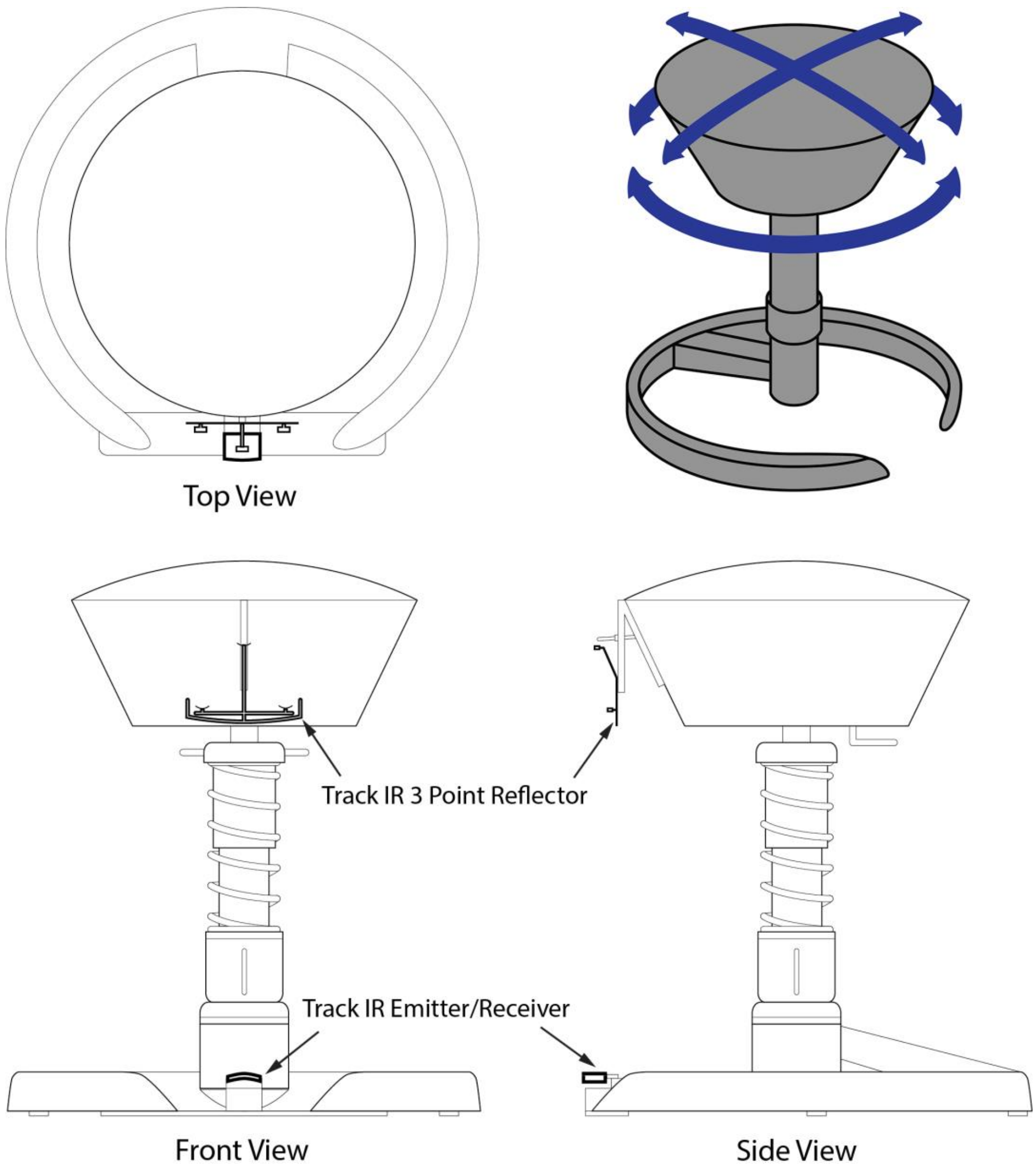


Figure 3.2. Photos of NaviChair Prototype

Within the virtual environment, our modified Swopper chair, which we call the NaviChair interface (Kitson et. al, 2015) allows users to move the user's position forward and backward by changing the chair's pitch and tilting the seat forward or backward, to strafe (move sideways) by changing the chair's roll and tilting the seat sideways, and to rotate the user's view orientation by deviating the chair's yaw from a central angle (see Figure 3.3). A velocity control motion model was used and user translation and rotation was transformed using an approximated quadratic transfer function. Maximum translation speed was 1.5 meters per second, while maximum rotation speed was 60° per second .

Figure 3.3. NaviChair schematic design



Additionally, we created a “pause” foot pedal for situations in which the user wishes to freeze the position to assess or discuss something. Though this can be useful in individual user scenarios, it is especially helpful during multi-user scenarios in which the user would like to freeze the scene and focus on an aspect of the design without requiring active control of the system.

3.2.3. BIM/3D Model Conversion

We decided to test our conversion process on the proposed Student Union Building (SUB) project at Simon Fraser University (SFU). This five story 100,000 square foot project was designed by the Vancouver offices of Perkins + Will using Autodesk Revit, a common BIM software tool. The software involved is used in many practices, and the building and project are of a common size for the firm. The conversion process, adapted from a report by researchers at the Penn State Computer Integrated Construction Group, involved a .fbx export from Revit, an import of the .fbx file into Autodesk 3dsMax, a .fbx export from 3dsMax, and finally a .fbx import into Unity3D (Yifan, 2014). Within Unity, collision detection, occlusion culling, and lightbaking features were implemented. See figure 3.4 below for a screenshot of the environment.

Figure 3.4. Unity Screenshot of the SFU Student Union Building

3.3. Interface Experimental Evaluation

In order to assess the usability and experience of our IVR representation interface in an architectural design evaluation scenario involving actual stakeholders of a building project, we chose to assess students within the environment of the proposed

SFU Student Union Building project. This type of scenario is closest to our future occupant testing scenario, and allowed us to test for usability issues as well. We chose not to engage in an evaluation of a design scenario involving clients or designers using the interface in process, as the basic usability of the interface needed to be assessed first in order to minimize risk of negatively affecting an actual design project. Also such design scenarios, especially one that might include gestural input components, are much larger in scope, and once basic usability concerns for our interface are addressed will be the subject of future work.

Our experiment compared two locomotion interfaces, a traditional joystick and our NaviChair locomotion interface, in combination with either an HMD (Oculus Rift DK2) or a 3D projection screen (Benq W1080ST). Given that our IVR representation interface system requirements include the facilitation of sensory immersion, the minimizing of motion sickness, the facilitation of user orientation and navigation, and the maximizing of learnability and controllability, we directed students to navigate through predetermined paths in the building, then at specific locations to point and estimate distances to each previously encountered location. In more specific terms we sought to answer these research questions and hypothesized these outcomes:

RQ 1) How do the NaviChair and joystick locomotion interfaces compare in terms of user performance on measures of spatial orientation, pointing task response time, and ratings of motion sickness, immersion, intuitiveness, and controllability?

H 1: The NaviChair will have better spatial orientation performance and lower pointing task response time than the joystick.

H 2: The NaviChair will have increased risk of motion sickness and have greater immersion ratings than the projection screen.

H 3: The joystick will have higher ratings of intuitiveness and controllability.

RQ 2) How do the HMD and 3D projection screen visual displays compare in terms of user performance on measures of spatial orientation, pointing task response time, and ratings of motion sickness and immersion?

H 4: The HMD will have better spatial orientation performance and lower pointing task response time than the joystick.

H 5: The HMD will have increased risk of motion sickness and have greater immersion ratings than the projection screen.

RQ 3) What interface preferences do users have for an IVR architectural design review scenario and do they believe our IVR representation tool would be useful?

H 6: The HMD and NaviChair will be favored for an IVR architectural design review scenario.

RQ 4) What feedback do users have on the NaviChair locomotion interface and how might the NaviChair be improved?

Previous research by Klatzky et al (1998) leads us to believe that our embodied locomotion interface will lead to improved spatial orientation performance and lower pointing task response times. Due to familiarity, we hypothesize that the joystick will be rated as more controllable and intuitive, and research done by Marchal et al., (2011) and also Beckhaus et al., (2007) leads us to hypothesize that an embodied locomotion interface will lead to improved ratings of immersion. Research done on visual displays leads us to hypothesize that use of the HMD will result in increased motion sickness (Sharples et al., 2008), though will be rated as more immersive than the projection screen (Ermi & Mäyrä, 2005; Schuemie et al., 2001). Due to the novelty of the Oculus Rift DK2 and the NaviChair, we hypothesize that students will find that this combination will be preferable for an architectural design review scenario.

3.3.1. Methods

The experiment was conducted according to a balanced 2x2 mixed factorial design, with the between-subjects independent variables of **visual display** type (HMD or Projection Screen) and gender, and the within-subjects independent variables of **locomotion interface** (NaviChair and joystick). See figure 3.5 below for a diagram of the experimental design. Our dependent variables were **spatial orientation performance**, **pointing response time,** and ratings of **immersion**, **motion sickness**, and interface **controllability** and **intuitiveness** (we use intuitiveness as a measure to inform our requirement of learnability). The procedure and analysis were partially based on previous work by Grechkin & Riecke (2014).

Figure 3.5. 2x2 Mixed Factorial Experimental Design

Participants

In total 32 participants (17 males, 15 females) took part in the experiment. Participants were selected as part of a convenience sample and consisted of undergraduate and graduate students at Simon Fraser University with ages ranging between 19-34 (M = 23.9). All participants had normal or corrected-to-normal vision and were naïve to the purposes of the experiment. One male participant was stereo blind.

The experiment was approved by the Office of Research Ethics at Simon Fraser University (REB #2012c0022), and was conducted according to the guidelines of the WMA Declaration of Helsinki. Each participant was informed of the risks involved, gave their written consent before the experiment, and was compensated with either $20.00 CAD or research credit as per their instructor's discretion.

Stimuli and Apparatus

Two locomotion interfaces were evaluated: our NaviChair interface (see Figures 3.2, 3.3) and a modified Logitech Freedom 2.4 radially symmetric vertically oriented joystick (see Figure 3.5). Visual displays consisted of an Oculus Rift DK2 and a Benq W1080ST 3D projection screen (see Figure 3.1), each having a comparable diagonal field of view (FOV) (Oculus Rift 110°; projection screen 90°). The projection screen had a vertical FOV of 50° and a horizontal FOV of 80°, while the Oculus Rift had a vertical FOV of 94.5° and a horizontal FOV of 84°. The user was seated 1.26 m from the projection screen, which was 2.12 m horizontally and 1.2 m vertically. Each visual display was used stereoscopically, and the Oculus Rift DK2 had a resolution of 960x1080 per eye, while the Benq W1080ST had a resolution of 1920x1080 per eye. The Oculus Rift DK2 had a refresh rate of 90 Hz, while the Benq W1080ST had a refresh rate of 144 Hz or 72 Hz per eye. Pointing and distance estimates were recorded by the modified Logitech Freedom 2.4 radially symmetric vertically oriented joystick also used a locomotion interface (see Firgure 3.5). Pointing was accomplished by tilting the joystick in the desired direction, and distance estimation was accomplished by tilting the joystick forwards to increase the estimate and backwards to decrease the estimate (the visual display showed the current estimate on screen).

The virtual environment presented 2 practice paths and 2 experimental paths through the SFU Student Union Building project (see Figure 3.7, 3.8). Both practice paths included 2 object locations, both experiment paths included 5 object locations, and there was at least one 90° turn between each location. Each location was randomly assigned an object, which was either a lamp, a train, a plane, a boot, a car, or a can of Coca-Cola (only one of each object was allowed per scene). Each path was assigned to a different floor to prevent any learning of the other task environments, each experiment path was organized in a pattern similar to a circle in order to make the results of the two environments more comparable, and each experiment path minimized any repeated views that might allow users to orient themselves by viewing recognizable locations more than once. This environment was imported from Revit 2014 into Unity 3D version 4.6, and was processed using an i7 3820 CPU, NVidia GTX 970 GPU, and 16 GB RAM at 60-75 frames per second (FPS).

Figure 3.6 Modified Logitech Freedom 2.4 radially symmetric joystick

Figure 3.7 **Practice Paths**

Note. Floor 4 (left) and floor 5 (right) of in the proposed Student Union Building at Simon Fraser University. Participants were asked to follow a red guiding sphere as it traveled along the red line, and encountered object locations at each blue square. At each location participants were asked to point and estimate distances to each previous location. Scale is roughly 1 mm = 1 m.

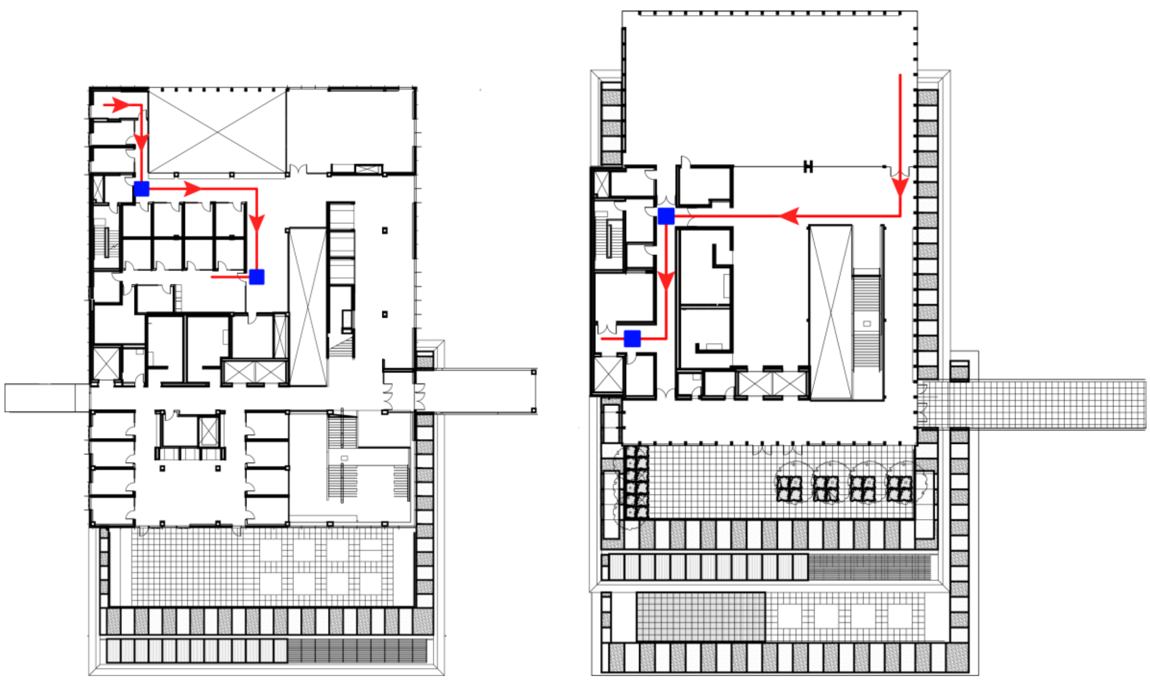


Figure 3.8. Main Experiment Paths

Note. Floor 1 (left) and floor 2 (right) of in the proposed Student Union Building at Simon Fraser University. Participants were asked to follow a red guiding sphere as it traveled along the red line, and encountered object locations at each blue square. At each location participants were asked ot point and estimate distances to each previous location. Scale is roughly 1 mm = 1 m.

Procedure

Informed Consent, Instructions, and Demonstration

After receiving written confirmation of informed consent, the participant's interpupillary distance (IPD) was measured, a test for stereo blindness was given, and a current rating of motion sickness between 0-100% was recorded.

The experimenter then demonstrated how their first locomotion interface functioned and how to complete their first practice environment (see Figure 3.7). For participants assigned to the HMD condition, the view was projected for the demonstration so both users could observe. Starting the task, users were instructed to remember their starting location, and then follow a red guiding sphere through the environment (see Figure 3.9) until they reached a virtual object rotating on top of a small table (see Figure 3.10).

Figure 3.9. Screenshot of Main Experiment Environment

Note. A view of the main task environment with a pointing location behind the red guiding sphere.

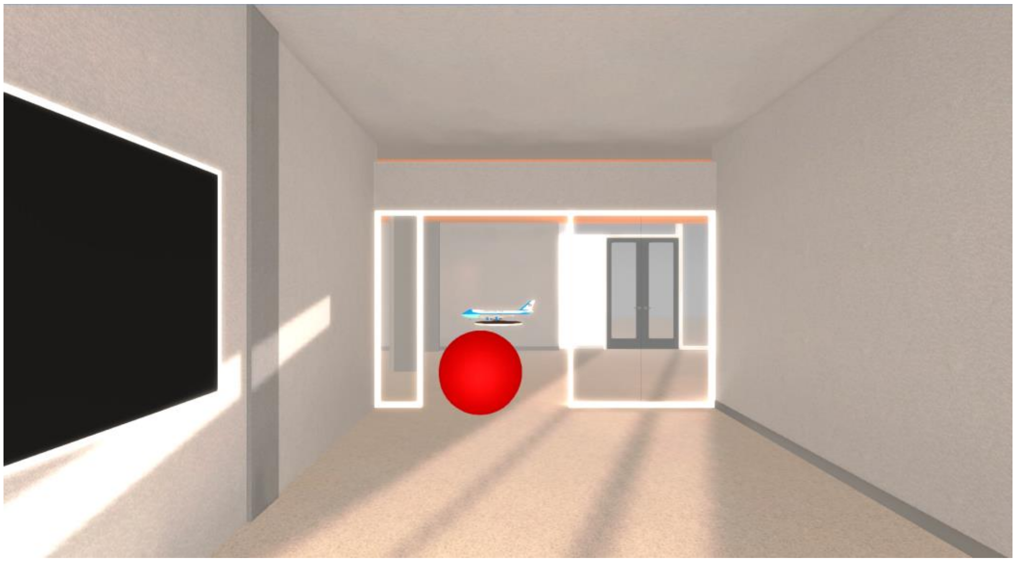
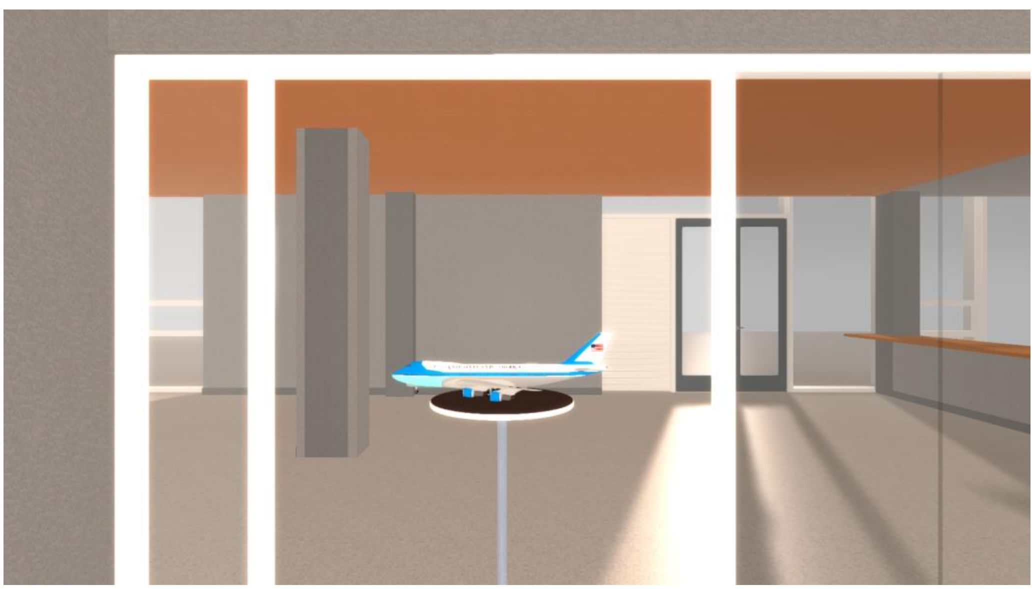


Figure 3.10. Screenshot of Main Experiment Environment Object Location

Note. A view of a main task environment pointing location.



This guiding sphere moved at the same speed as the maximum user translation speed of 1.5 meters per second, and was not allowed to travel more than 2.5 meters from the user's furthest location along the path. Once within a 1.5 meter range of the object, user position translation was temporarily frozen. Participants were then given a demonstration of the pointing and distance estimation procedure, which conveyed the participant's pointing response via their angling of a radially symmetric vertically oriented joystick located in front of them (see Figures 3.6, 3.11, 3.12). To point to a location, participants were instructed to angle the joystick towards where they wanted to point. Following this participants were asked to estimate the straight line distance to a location, by increasing or decreasing the estimate displayed on screen by pushing the joystick forward (to increase the estimate) or and backward (to decrease the estimate). Once satisfied with the estimate, participants were directed to push a confirmation button on the joystick to record the response. This pointing and distance estimation procedure completed for each location. The location to point and estimate distances towards was indicated by a text to speech voice command and a small version of the object displayed. The experimenter then moved the locomotion interface to the next practice location, in which the participant was given a demonstration on how to point and estimate the distance to both the previous location and the initial starting location. The experimenter confirmed there were no questions and the experiment continued, this time with the participant operating alone.

VR Session 1: First Interface

Following this initial demonstration of the experiment procedure, the practice path task was restarted and participants were directed to complete it on their own after becoming acquainted with the locomotion interface (see Figure 3.7). Just as was previously demonstrated, participants followed the red guiding sphere to each object location. At each location text to speech instructions asked participants to point and estimate the distance to each previous location (the order asked was randomized), and then text to speech instructions instructed participants to follow the guiding sphere to the next location. Once this practice phase was complete, participants were then asked if they were experiencing any motion sickness or discomfort. Upon confirmation that this was not the case, participants were then asked to complete a main experiment task environment (see Figure 3.8), which involved 5 object locations requiring pointing and distance estimation responses. After completion of this task, participants were asked to rate their motion sickness and to draw a map of this new guided path environment (see Appendix C.3).

Figure 3.11. HMD with NaviChair (left) & 3D projection screen with NaviChair (right)

Figure 3.12. HMD with joystick (left) & 3D projection screen with joystick (right)

VR Session 2: Second Interface

Once the initial locomotion interface task was complete, a short explanation of the new interface was given. The experiment then continued into a second practice task environment that also included two object locations (see Figure 3.7), and followed the same procedure as the first. After this second practice task was completed, participants were once again asked to rate their experience of motion sickness, and the experiment continued into the second main task environment (see Figure 3.8). Following the same procedure as the first guided main task environment, participants followed the guiding sphere to each of the 5 locations and recorded their responses with the joystick apparatus. Upon completion, participants drew another map of their path in the main experiment environment and rated their experience of motion sickness.

Post-experimental Data Gathering: Visual Display Comparison, Ratings, and Interview

After the main phase of the experiment was complete, participants were given the other visual display interface (e.g., if in the HMD condition, they used the 3D projection screen) and completed a practice task environment (see Figure 3.7) using the NaviChair locomotion interface. Participants were informed that this trial is only for them to compare with the other visual display, and that they should note the differences between the two. Once participants completed this other visual display interface they were asked to rate their motion sickness a final time.

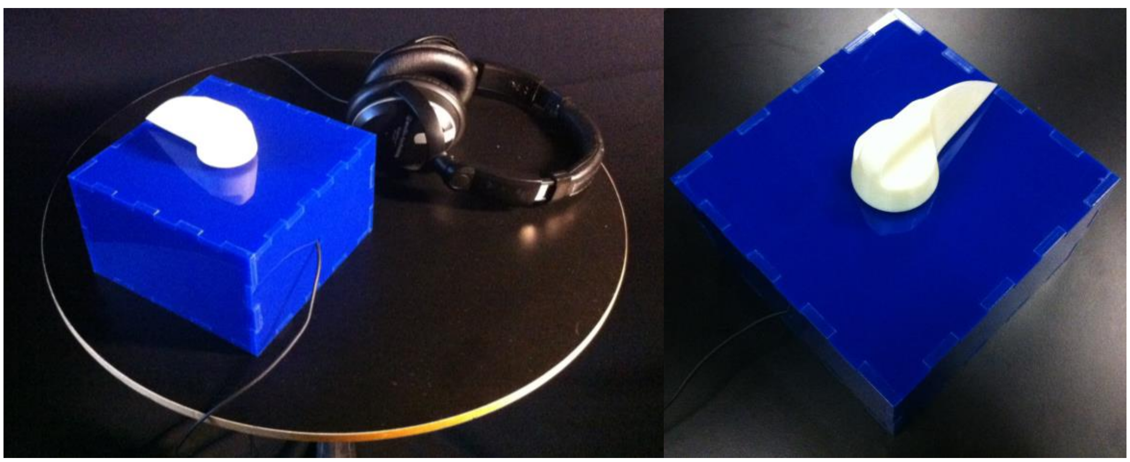
Following the virtual reality phase of the experiment, participants were then asked to respond to a number of questions in a post-experiment interview. These questions included an questions relating to gaming experience and frequency, ratings of how immersed they felt with the different interfaces, ratings of how controllable and intuitive they thought the interfaces were, rating of their real world orientation ability, and any other comments or concerns they have with any of the interfaces encountered (see Appendix C.2 for the complete list of questions). This questionnaire was designed for the purposes of this study, so the validity and reliability of these measures has not been assessed.

Real-world Spatial Orientation Experiment and Debriefing

Finally, in order to compare virtual spatial orientation performance with real world spatial orientation performance for correlation, participants were asked to respond to a real world orientation task at the SFU Surrey campus. This real world task used a different pointing device from the virtual task. Participants were guided around a 100 meter radius from the laboratory to 6 different locations marked by a shape on the wall. At each location a pointing task and distance estimation task occurred, directing users to point to previously visited locations in random order. This task was recorded using a pointing box with a rotary encoder and dial for pointing toward each location (see Figure

3.12), and was placed against a wall for reference at each point. The joystick was not used due to difficulty with relative placement with the respect to the user, as well as the need to carry a bulky computer for the recording of data. The major differences between the VR pointing task and the real world pointing task were related to the use of a different pointing device, and differences in the task environment. In the VR task, the turns were mainly 90°, and in the real world task, the majority of turns were not 90° and the some of the paths were curved. This was due to the fact that the campus building was designed in a different style from the proposed Student Union Building, with the former being much more curvilinear in its form and circulation paths. Following this task, participants answered questions regarding their familiarity with the campus and their own beliefs about their real world orientation ability. After this, participants were then debriefed and compensated for their time.

Figure 3.13. Pointing Box for Real World Orientation Comparison



Measures and Analysis

Spatial Orientation Performance Measures

Participants' **spatial orientation performance** was quantified using three types of pointing error measurements given the ratio data type pointing angles measured from the joystick. Because all participants were measured under a number of different conditions in both between-subjects and within-subjects, all differences in spatial orientation measures were analyzed using a 2x2 mixed-design ANOVA.

Mean absolute pointing error: measures overall accuracy of the participants with the arithmetic mean of absolute pointing errors for all targets at a given location (Grechkin & Riecke, 2014).

Absolute ego error: measures systematic bias in pointing errors that can serve as an estimate of the error in participants' perceived self-orientation (Batschelet, 1981).

Configuration error: measures variability of pointing estimates and serves as an estimate of consistency for relative directions to multiple target objects (Riecke, Heyde, & Bülthoff, 2005; Wang & Spelke, 2000).

Pointing task response time: The time participants took to respond to each request to point to a given location was recorded and assessed using a repeated measures ANOVA to test for equality of means. This data was ratio type.

Motion Sickness, Immersion, Controllability, and Intuitiveness Measures

Measures of interface influence on **motion sickness**, **immersion**, **controllability,** and **intuitiveness** were assessed using a 0-100% rating scale. These measures were each interval type data. Because participants were measured under a number of different conditions, we assessed results using a repeated-measures ANOVA to test for equality of means.

Post-experiment Interview

Qualitative post-experiment data included open questions regarding the ease of use of the interfaces and generally sought to gather information on comparisons and inform future redesign of the Navi-Chair. These questions included:

"Which locomotion interface was more difficult? Why?"

"Which locomotion interface was easier? Why?"

"For the Swopper chair, which display was easier to use it with?"

> “Overall, would you prefer to use the chair or joystick for navigating this virtual world (a virtual architectural design)? Why? Please elaborate.”

> “What did you think of the physical motion used from the chair? What was best/worst about it? How could it be improved?”

Notes were made on the participant’s responses, which were evaluated informally by the experimenter. The validity and reliability of these questions was not assessed.

3.3.2. Results

Each combination of locomotion and display interfaces was analyzed for differences in user orientation performance, motion sickness, interface controllability and immersion, and interface preference within an architectural design review scenario. All data was normally distributed and was analyzed using parametric tests, and only significant effects are reported.

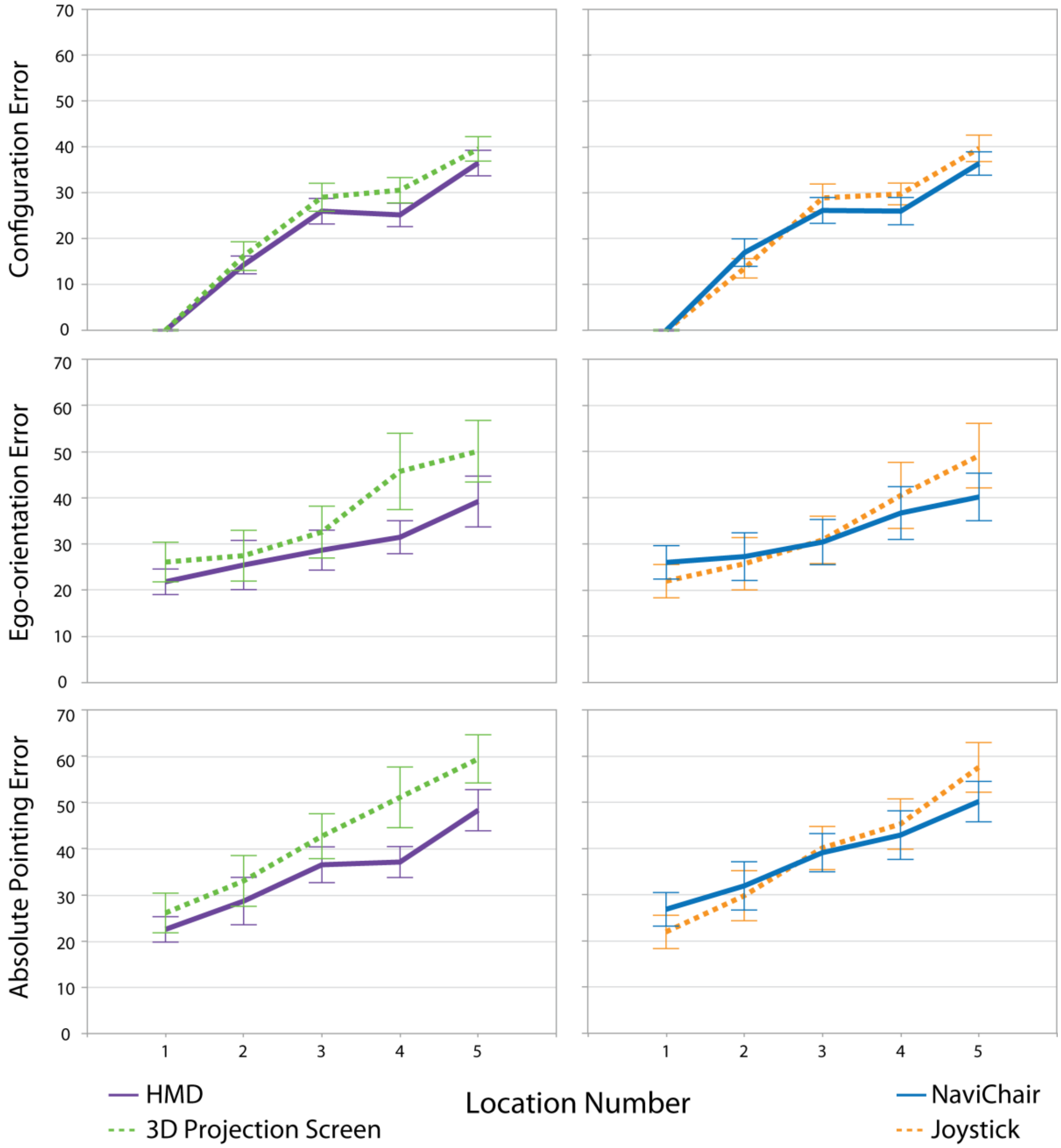
Quantitative Analysis

Spatial Orientation Performance

We analyzed the dependent variable measures of mean absolute pointing error, absolute ego-orientation error, and configuration error to look for significant differences for each according to the independent variables of locomotion interface (within), visual display (between), gender (between), and location (within) using a mixed-design 2x2x2x5 ANOVA.

Figure 3.14 Mean Orientation Measures for Interfaces at Each Location

Note. Whiskers indicate one standard error



Mean Absolute Pointing Error

A test of between-subjects effects revealed display to be a significant factor for mean absolute pointing error, indicating that orientation for the Oculus Rift HMD (M = 34.78, SE = 2.58) was significantly better than the 3D projection screen (M = 42.46, SE = 2.54), $F(1, 139) = 4.500$, $p = .036$, $\eta^2 = .031$. A moderate partial eta squared effect size (Cohen, 1992) was observed, showing that the visual display condition effect accounts for 3.1% of the variance. See Figure 3.16 below for graphs comparing mean absolute pointing error.

A significant interaction between locomotion interface and gender was found, indicating that the mean absolute error for different genders using the NaviChair and the joystick were significantly different. That is, females have a lower mean absolute pointing error using the NaviChair (M = 38.39, SE = 3.04) compared to the joystick (M = 44.97, SE = 3.24), and males had a higher mean absolute pointing error using the NaviChair (M = 37.57, SE = 2.83) compared to the joystick (M = 33.58, SE = 3.01), $F(1, 139) = 5.280$, $p = .023$, $\eta^2 = .037$. A moderately small effect size was observed, showing the interaction between gender and locomotion interface accounts for 3.7% of the variance. See Figure 3.17 below for graphs of mean orientation measures for gender and locomotion interface.

A significant effect was found for location, $F(4, 139) = 7.862$, $p < .001$, $\eta^2 = .184$, indicating that mean absolute pointing error was significantly different depending on the which object location the observer was at. The effect size is moderate, with location accounting for 18.4% of the variance. Post hoc tests found that location 1 had significantly lower mean absolute error than locations 4 ($p = .008$) and 5 ($p < .001$), and location 2 had significantly lower mean absolute error than location 5 ($p = .001$). See Figure 3.15 above for graphs of mean orientation measures for each location and see Table 2 below for a summary of the mean absolute pointing error analysis.

Absolute Ego-Orientation Error

A significant main effect for the interaction between locomotion interface and gender was found, indicating that absolute ego-orientation error were significantly lower for females using the NaviChair (M = 31.44, SE = 3.29) compared to the joystick (M = 39.35, SE = 3.82), while males had a higher ego-orientation error using the NaviChair (M = 32.33, SE = 3.09) compared to the joystick (M = 28.13, SE = 3.58), $F(1, 140) = 5.723$, $p = .018$, $\eta^2 = .039$. A moderate effect size was observed, showing that the interaction between gender and locomotion interface accounts for 3.9% of the variance. See Figure 3.17 below for graphs of mean orientation measures for gender and locomotion interface.

Location was found to be a significant factor, $F(4, 140) = 3.523$, $p = .009$, $\eta^2 = .091$, signifying that the effect of location on ego-orientation error was moderate. Post hoc tests revealed location 5 had significantly ego-orientation error than locations 1 (p = .017) and 2 (p = .050). See Figure 3.15 below for graphs of mean orientation measures for each location and see Table 3 below for a summary of the absolute ego-orientation error analysis.

Configuration Error

A test for within-subjects effects for locomotion interface revealed no significant main effects. Location was found to be a significant factor, $F(4, 140) = 63.443$, $p < .001$, $\eta^2 = .644$, indicating that configuration error was significantly different depending on the which object location the observer was at, i.e., whether they were first, second, third, etc. The effect size is large, indicating that the effect of location accounts for 64% of the variance. To further examine the effect of location, we conducted post hoc tests. We found that participants had significantly lower mean configuration error for the second location compared to the 3rd ($p < .001$), 4th ($p < .001$), and 5th ($p < .001$) locations. Furthermore, the third and fourth locations also showed significantly lower error than the 5th location (both $p = .001$). See Figure 3.15 below for graphs of mean orientation measures for each location. All other effects, main effects and interactions, were non-significant and see Table 4 below for a summary of the configuration error analysis.

Pointing Task Response Time

A two way repeated measures ANOVA was used to evaluate pointing response time at each location, but did not find any significant effects between either the locomotion interfaces or the visual display conditions. The analysis results are displayed below in Figure 3.14 and see Table 1 below for a summary of the pointing response time analysis.

Figure 3.15 Mean Pointing Response Time

Note. Whiskers indicate one standard error

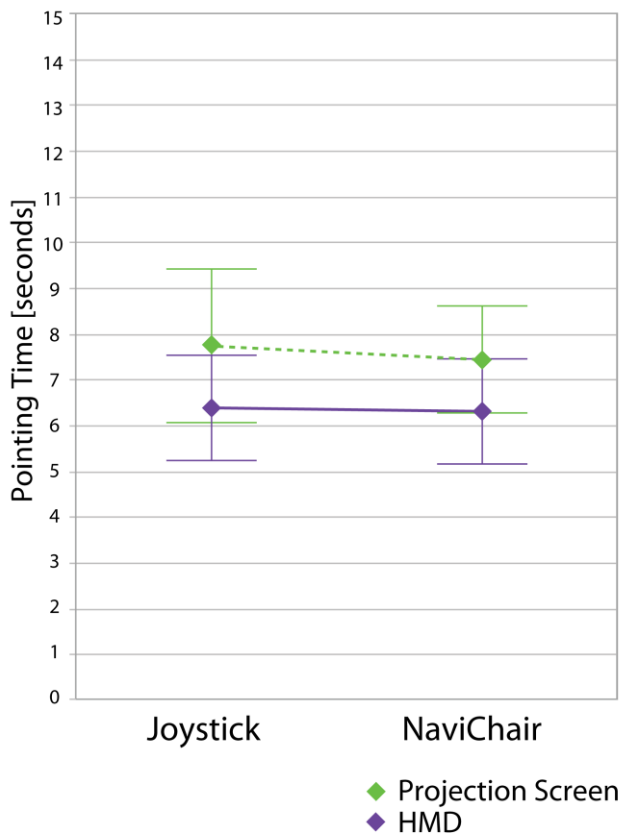


Table 1. Results for Pointing Task Response Time (significant effects are italicized)

Effect: Pointing Time	Degrees of Freedom	*F* value	*p*-value	Partial Eta Squared	Observed Power
Locomotion Interface	1	.099	.755	.003	.061
Locomotion Interface * Visual Display	1	.035	.854	.001	.054
Visual Display	1	.508	.482	.017	.106

Figure 3.16 Mean Orientation Measures for Interface Combinations

Note. Whiskers indicate one standard error

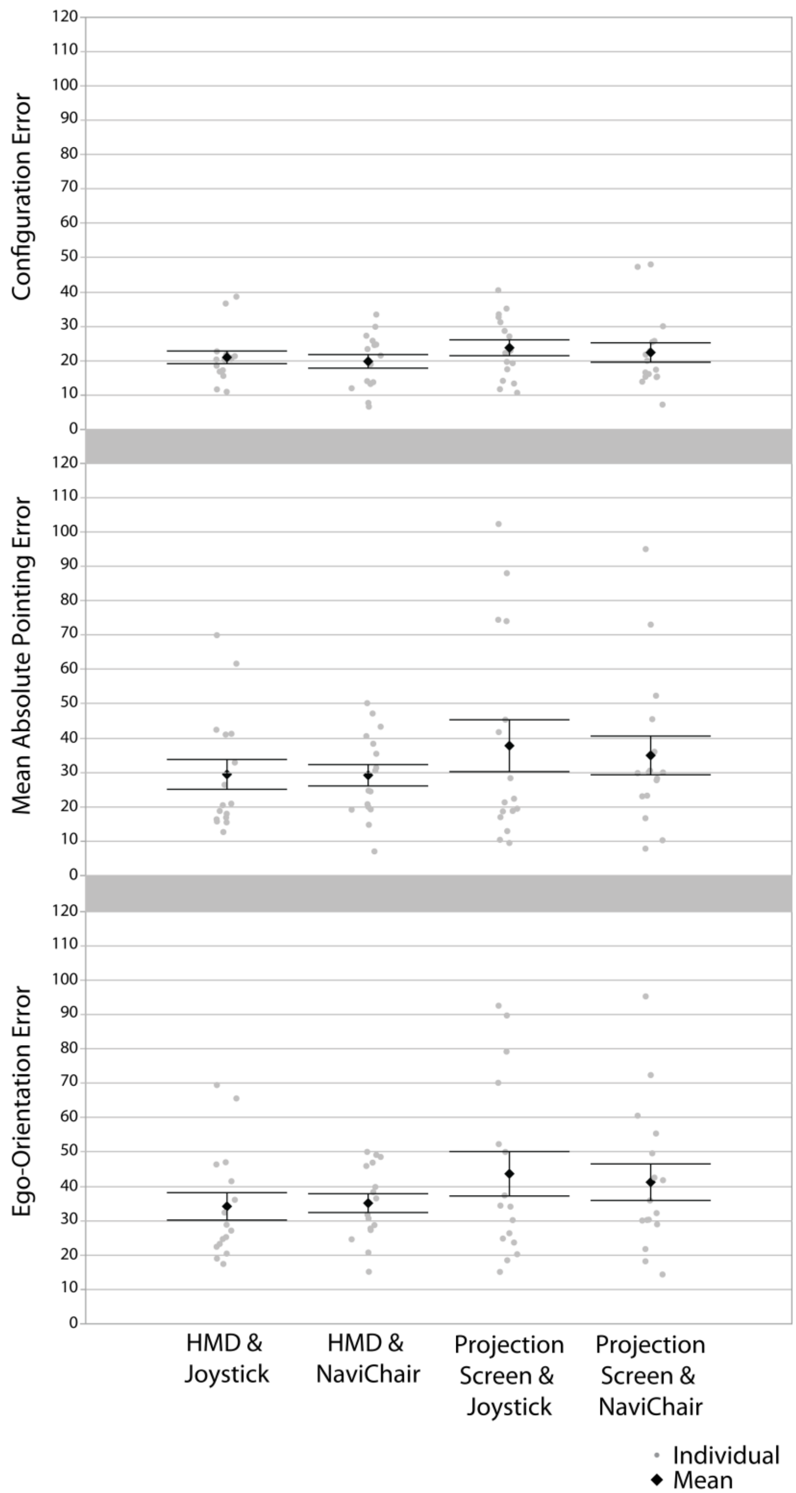


Figure 3.17 Mean Orientation Measures for Locomotion Interfaces by Gender

Note. Whiskers indicate one standard error

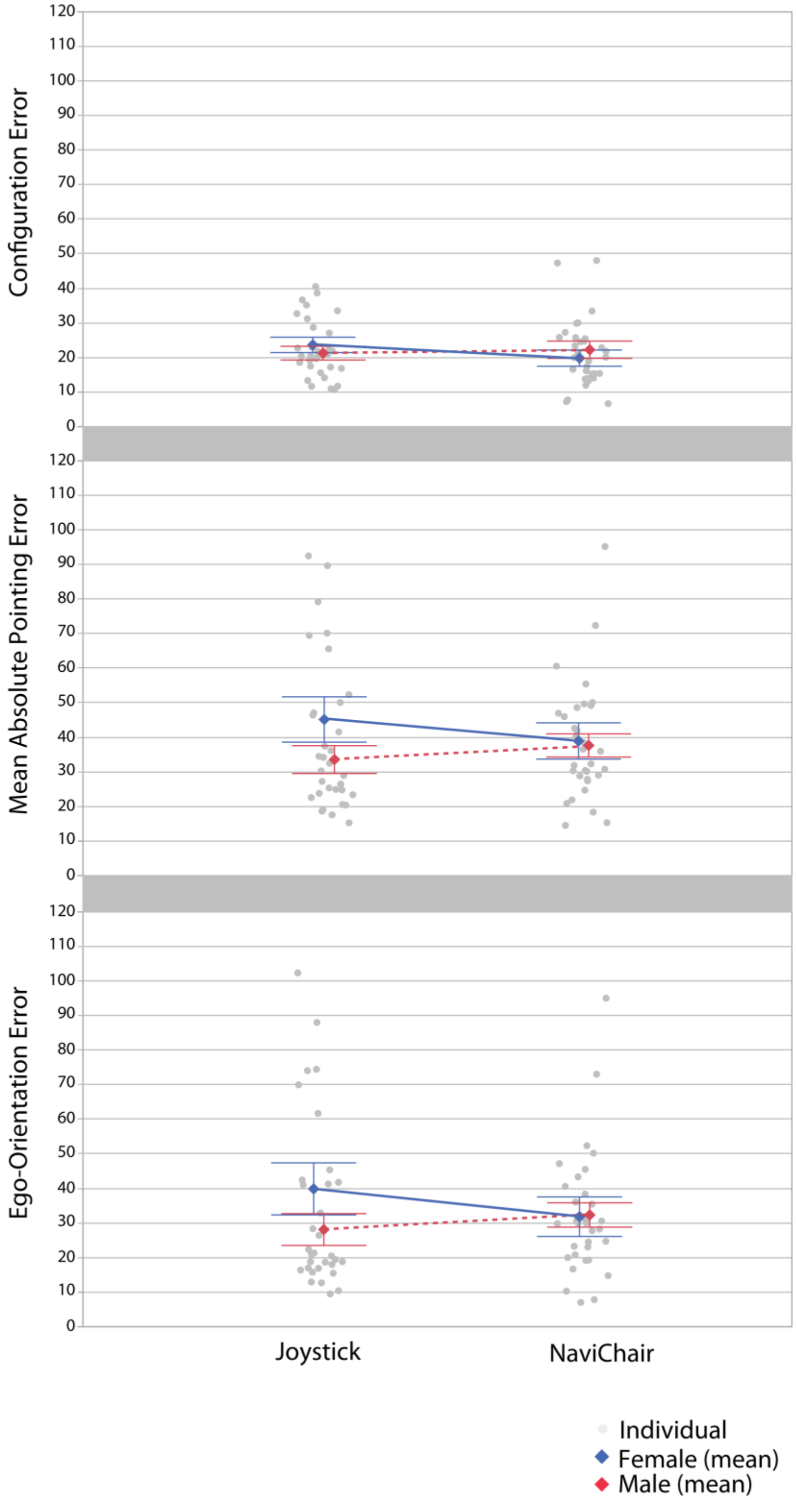


Table 2. **Results for Mean Absolute Pointing Error (significant effects are italicized)**

Effect: Mean Absolute Error	Degrees of Freedom	*F* value	*p*-value	Partial Eta Squared	Observed Power
Locomotion Interfaces	1	.316	.575	.002	.086
Locomotion Interfaces * Location Number	4	.754	.557	.021	.238
*Locomotion Interfaces * Gender*	*1*	*5.280*	*.023*	*.037*	*.626*
Locomotion Interfaces * Visual Display	1	.253	.616	.002	.079
Locomotion Interfaces * Location Number * Gender	4	.167	.955	.005	.084
Locomotion Interfaces * Location Number * Visual Display	4	.492	.741	.014	.165
Locomotion Interfaces * Gender * Visual Display	1	.047	.828	.000	.055
Locomotion Interfaces * Location Number * Gender * Display	4	.163	.957	.005	.083
Location Number	*4*	*7.862*	*.000*	*.184*	*.997*
Gender	1	2.843	.094	.020	.388
Visual Display	*1*	*4.500*	*.036*	*.031*	*.558*
Location Number * Gender	4	.793	.532	.022	.249
Location Number * Visual Display	4	.334	.855	.010	.124
Gender * Visual Display	1	3.258	.073	.023	.434
Location Number * Gender * Visual Display	4	.811	.520	.023	.254

Table 3. **Results for Absolute Ego-Orientation Error (significant effects are italicized)**

Effect: Absolute Ego Error	Degrees of Freedom	*F* value	*p*-value	Partial Eta Squared	Observed Power
Locomotion Interfaces	1	.534	.466	.004	.112
Locomotion Interfaces * Location Number	4	.864	.487	.024	.270
*Locomotion Interfaces * Gender*	*1*	*5.723*	*.018*	*.039*	*.661*
Locomotion Interfaces * Visual Display	1	.147	.702	.001	.067
Locomotion Interfaces * Location Number * Gender	4	.175	.951	.005	.086
Locomotion Interfaces * Location Number * Visual Display	4	.161	.958	.005	.083
Locomotion Interfaces * Gender * Visual Display	1	.138	.711	.001	.066
Locomotion Interfaces * Location Number * Gender * Display	4	1.092	.363	.030	.337
Location Number	*4*	*3.523*	*.009*	*.091*	*.856*
Gender	1	1.527	.219	.011	.233
Visual Display	1	2.954	.088	.021	.400
Location Number * Gender	4	.753	.557	.021	.238
Location Number * Visual Display	4	.271	.896	.008	.108
Gender * Visual Display	1	2.800	.097	.020	.383
Location Number * Gender * Visual Display	4	.788	.535	.022	.248

Table 4. **Results for Configuration Error (significant effects are italicized)**

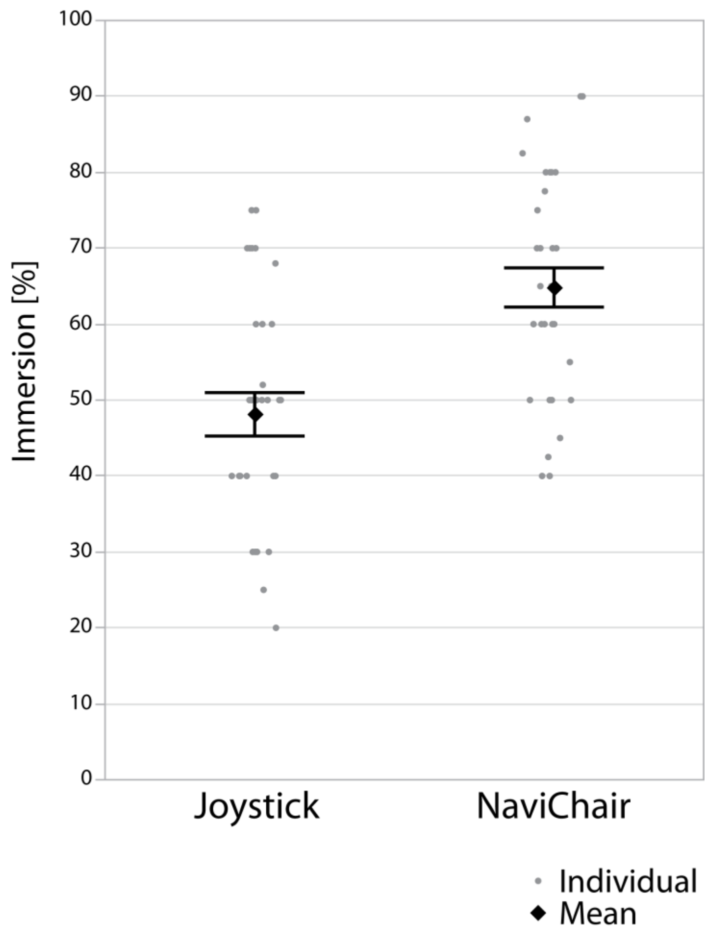
Effect: Configuration Error	**Degrees of Freedom**	***F* value**	***p*-value**	**Partial Eta Squared**	**Observed Power**
Locomotion Interfaces	1	1.126	.290	.008	.184
Locomotion Interfaces * Location Number	4	.766	.549	.021	.241
Locomotion Interfaces * Gender	1	2.654	.106	.019	.366
Locomotion Interfaces * Visual Display	1	.020	.889	.000	.052
Locomotion Interfaces * Location Number * Gender	4	1.318	.266	.036	.403
Locomotion Interfaces * Location Number * Visual Display	4	1.035	.391	.029	.320
Locomotion Interfaces * Gender * Visual Display	1	3.015	.085	.021	.407
Locomotion Interfaces * Location Number * Gender * Display	4	.314	.868	.009	.119
Location Number	*4*	*63.443*	*.000*	*.644*	*1.000*
Gender	1	0.12	.912	.000	.051
Visual Display	1	2.548	.113	.018	.354
Location Number * Gender	4	.655	.624	.018	.210
Location Number * Visual Display	4	.306	.874	.009	.117
Gender * Visual Display	1	.634	.427	.005	.124
Location Number * Gender * Visual Display	4	.427	.789	.012	.148

Immersion Ratings

Using a two way repeated measures ANOVA, a within-subjects main effect was found for locomotion interface condition and immersion ratings. The joystick resulted in lower mean immersion ratings (*M* = 48.13, *SE* = 2.91) compared to the (*M* = 64.83, *SE* = 2.28), $F(1, 30) = 25.854$, $p < .001$, $\eta^2 = .463$. A large effect size was observed, with 46.3% of the variance accounted for by the locomotion interface condition. These results are displayed below in Figure 3.18.

Figure 3.18 Mean Immersion of Locomotion Interface Ratings

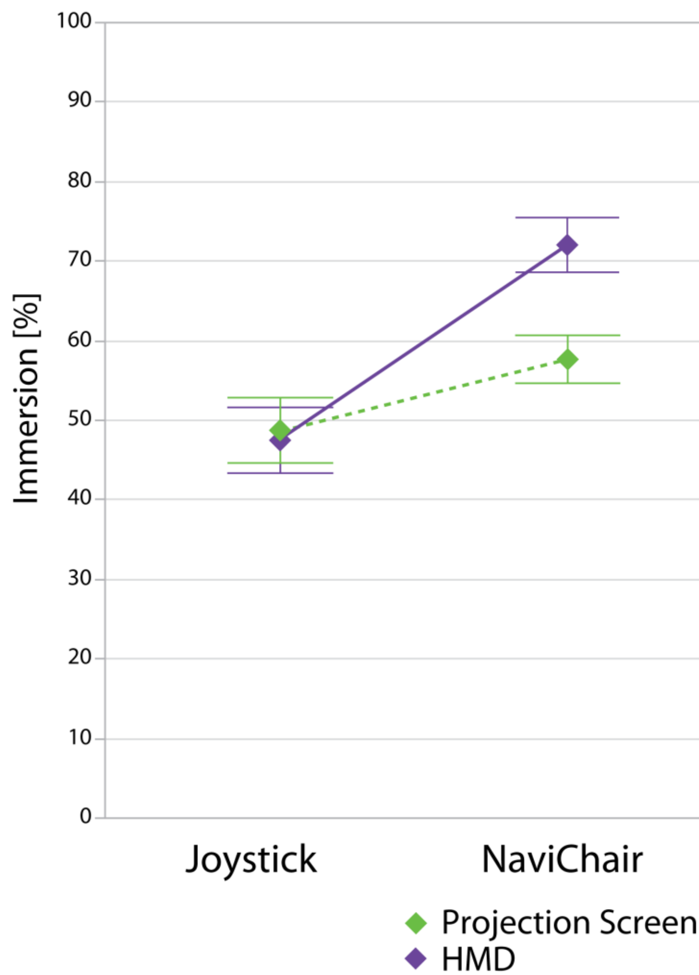
Note. Whiskers indicate one standard error



Additionally, a significant interaction between locomotion interface and visual display interface was found, indicating that the mean immersion ratings for the combination of the HMD and NaviChair (M = 72.0, SE = 3.22) were significantly higher from the mean ratings of the HMD and joystick (M = 47.5, SE = 4.109), the projection screen and NaviChair (M = 57.7, SE = 3.22), and the projection screen and the joystick (M = 48.8, SE = 4.11), $F(1, 30) = 5.633$, $p = .024$, $\eta^2 = .158$. A large effect size was observed, showing that the locomotion interface accounts for 15.8% of the variance. These results are displayed below in Figure 3.19. See Table 4 below for a summary of the immersion rating analysis.

Figure 3.19 Mean Locomotion and Visual Display Immersion Ratings

Note. Whiskers indicate one standard error

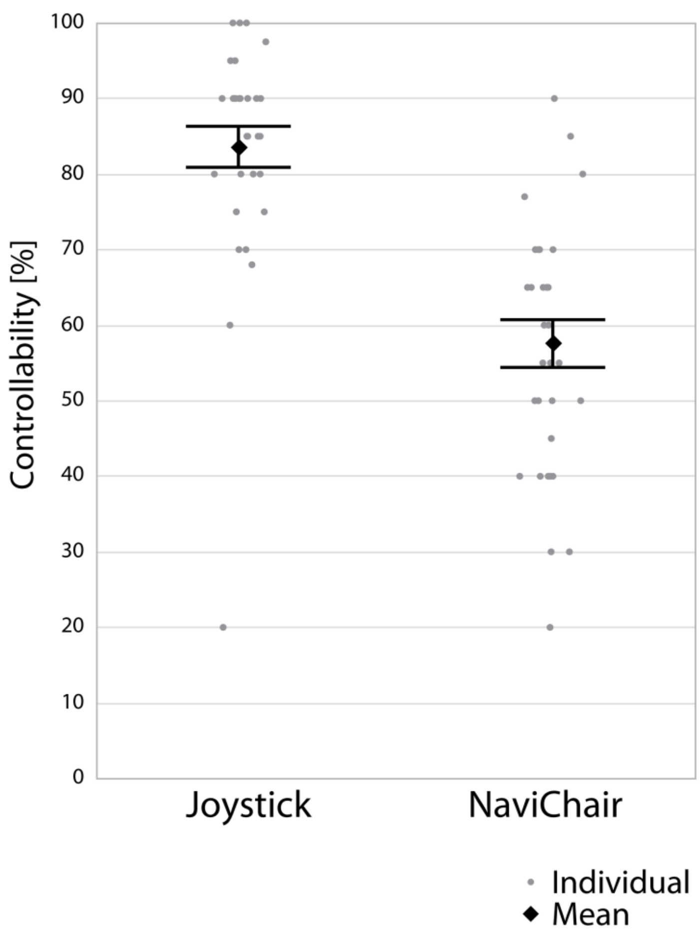


Controllability Ratings

A two way repeated measures ANOVA was used to discover a within-subjects main effect for locomotion interface condition and user rating of controllability. It revealed the joystick resulted in higher mean controllability ratings (*M* = 83.61, *SE* = 2.76) compared to the NaviChair (*M* = 57.56, *SE* = 3.21), $F(1, 30) = 50.610$, $p < .001$, $\eta^2 = .628$. A very large effect size was observed, showing that the locomotion interface accounts for 62.8% of the variance. These results are displayed below in Figure 3.20. See Table 5 below for a summary of the controllability rating analysis.

Figure 3.20 Mean Locomotion Interface Controllability Ratings

Note. Whiskers indicate one standard error

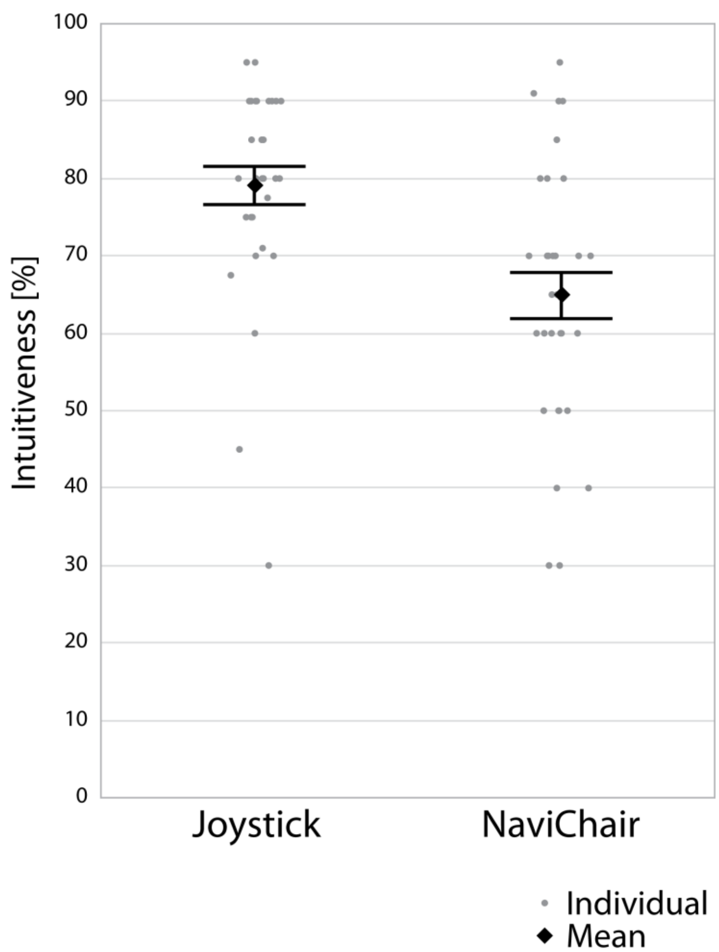


Intuitiveness

Also using a two way repeated measures ANOVA, a within-subjects main effect was found for locomotion interface condition and intuitiveness ratings. It revealed the joystick resulted in higher mean intuitiveness ratings (M = 79.10, SE = 13.96) compared to the NaviChair (M = 64.88, SE = 16.88), $F(1, 30) = 23.065$, $p < .001$, $\eta^2 = .435$. A large effect size was observed, with 43.5% of the variance was accounted for by the locomotion interface condition. These results are displayed below in Figure 3.21. See Table 5 below for a summary of the intuitiveness rating analysis.

Figure 3.21 Mean Locomotion Interface Intuitiveness Ratings

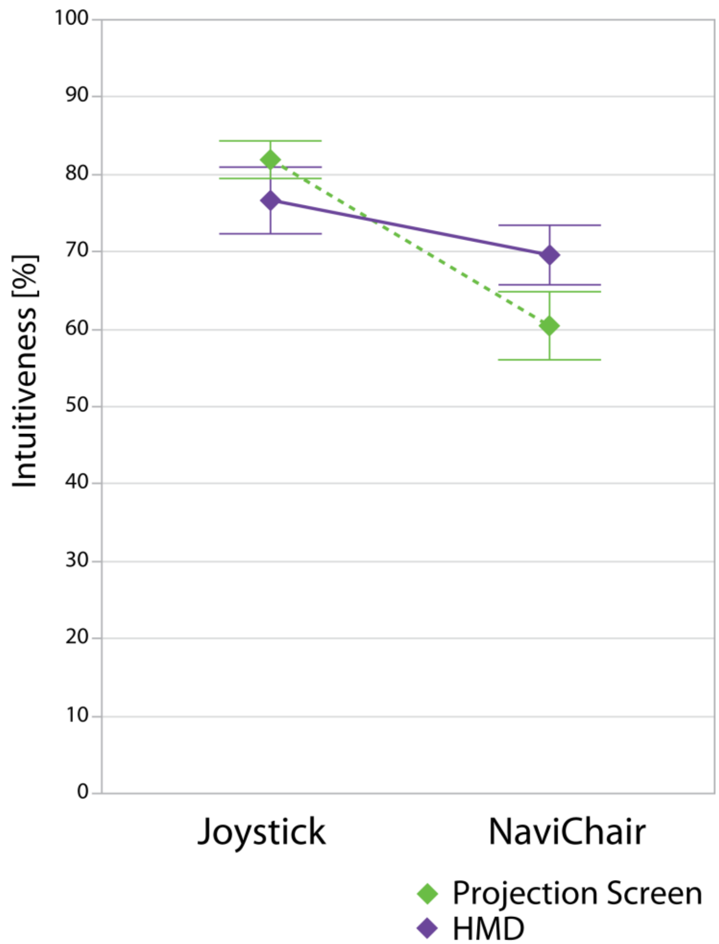
Note. Whiskers indicate one standard error



A significant interaction between locomotion interface and visual display interface was also found, indicating that the mean intuitiveness ratings for the projection screen and the joystick (*M* = 81.72, *SE* = 2.42) were significantly higher from the mean ratings of the HMD and joystick (*M* = 76.47, *SE* = 4.29), the projection screen and NaviChair (*M* = 60.31, *SE* = 4.39), and the combination of the HMD and NaviChair (*M* = 69.44, *SE* = 3.84), $F(1, 30) = 5.894$, $p = .021$, $\eta^2 = .164$. A moderate effect size was observed, showing that the locomotion interface accounts for 16.4% of the variance. These results are displayed below in Figure 3.22.

Figure 3.22 Mean Locomotion and Visual Display Intuitiveness Ratings

Note. Whiskers indicate one standard error



Motion Sickness

Ratings of motion sickness for each interface combination were analyzed using a two way repeated measures ANOVA, which revealed a significant between-subjects main effect for visual display condition. It revealed the HMD resulted in higher mean motion sickness ratings (*M* = 22.45, *SE* = 3.60) compared to the projection screen (*M* = 6.19, *SE* = 3.60), $F(1, 30) = 10.189$, $p = .003$, $\eta^2 = .254$. A large effect size was observed, with the visual display condition accounts for 25.4% of the variance. Locomotion interface did not significantly influence the experience of motion sickness and no interaction was observed. These results are displayed below in Figure 3.23. See Table 5 below for a summary of the motion sickness rating analysis.

Figure 3.23 Mean Motion Sickness Ratings

Note. Whiskers indicate one standard error

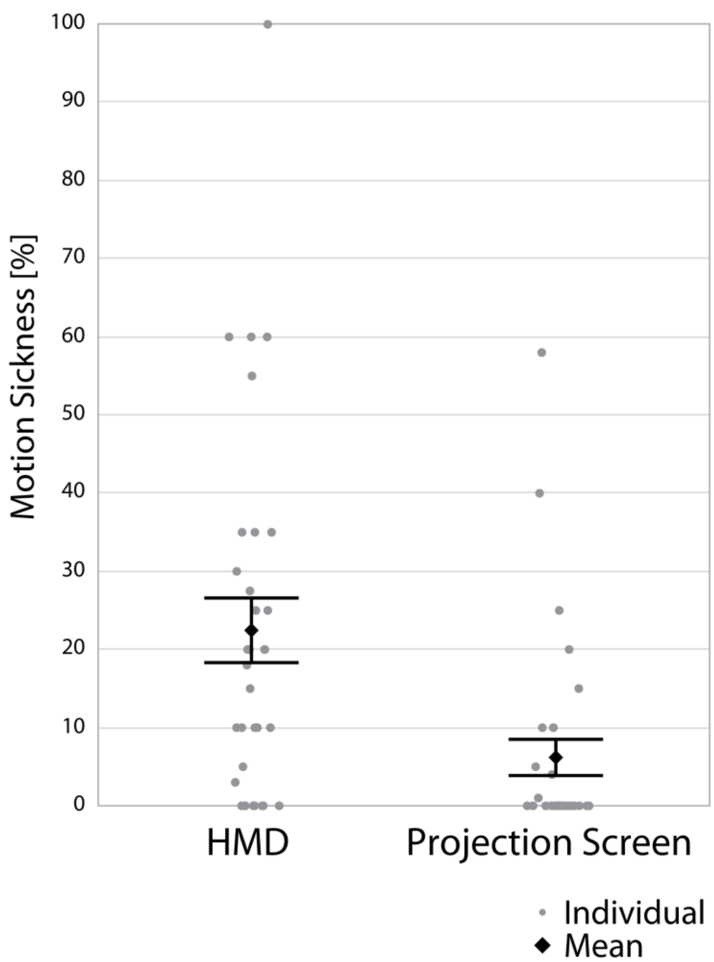


Table 5. Results for Ratings of Immersion, Controllability, Intuitiveness, and Motion Sickness

(significant effects are italicized)

Effect: Immersion	**Degrees of Freedom**	***F* value**	***p*-value**	**Partial Eta Squared**	**Observed Power**
Locomotion Interface	*1*	*25.854*	*.000*	*.463*	*.998*
*Locomotion Interface * Visual Display*	*1*	*5.633*	*.024*	*.158*	*.632*
Visual Display	1	2.603	.117	.080	.345

Effect: Controllability	**Degrees of Freedom**	***F* value**	***p*-value**	**Partial Eta Squared**	**Observed Power**
Locomotion Interface	*1*	*50.610*	*.000*	*.628*	*1.000*
Locomotion Interface * Visual Display	1	.000	.990	.000	.050
Visual Display	1	.061	.806	.002	.057

Effect: Intuitiveness	**Degrees of Freedom**	***F* value**	***p*-value**	**Partial Eta Squared**	**Observed Power**
Locomotion Interface	*1*	*23.065*	*.000*	*.435*	*.996*
*Locomotion Interface * Visual Display*	*1*	*5.894*	*.021*	*.164*	*.652*
Visual Display	1	.184	.671	.006	.070

Effect: Motion Sickness	**Degrees of Freedom**	***F* value**	***p*-value**	**Partial Eta Squared**	**Observed Power**
Locomotion Interface	1	.973	.332	.031	.159
Locomotion Interface * Visual Display	1	.904	.349	.029	.151
Visual Display	*1*	*10.189*	*.003*	*.254*	*.870*

Real World Orientation Performance

A multiple regression was run to assess correlations between real world ego-orientation error and predictor variables. In order to compare virtual and real world orientation performance, predictor variables included joystick (virtual) ego-orientation error and NaviChair (virtual) ego-orientation error. Also, gender, spatial ability estimates, SFU familiarity, and participant's self-assessed real world performance estimates were also evaluated as predictor variables for correlation with real world ego-orientation error. These variables did not statistically significantly predict real world ego-orientation error, $F(7,62) = .854$, $p = .854$, $R^2 = -.057$. None of the variables added statistically significantly to the prediction, $p > .05$.

A multiple regression was run to assess correlations between real world configuration error and predictor variables. In order to compare virtual and real world orientation performance, predictor variables included joystick (virtual) ego-orientation error and NaviChair (virtual) ego-orientation error. Also, gender, spatial ability estimates, SFU familiarity, and participant's self-assessed real world performance estimates were also evaluated as predictor variables for correlation with real world configuration error. These variables statistically significantly predicted real world configuration error, $F(7,62) = 2.614$, $p = .020$, $R^2 = .141$. Joystick (virtual) configuration error was the only variable that was correlated with real world configuration error, $p = .038$. This indicates that users who performed poorly with the joystick also performed poorly in the real world orientation task.

A multiple regression was run to assess correlations between real world mean absolute error and predictor variables. In order to compare virtual and real world orientation performance, predictor variables included joystick (virtual) ego-orientation error and NaviChair (virtual) ego-orientation error. Also, gender, spatial ability estimates, SFU familiarity, and participant's self-assessed real world performance estimates were also evaluated as predictor variables for correlation with real world mean absolute error. These variables statistically did not significantly predict real world mean absolute error, $F(7,62) = .548$, $p = .794$, $R^2 = -.048$. None of the variables added statistically significantly to the prediction, $p > .05$.

Qualitative Analysis

Ease of Use

As seen in the quantitative results, the majority (91%) of participants found the NaviChair to be more difficult to control. Participants described a number of factors that affected their ability to control the interface, with most users tending to desire either more or less sensitivity to rotation and translation. Four participants in particular found the motion mapping to be strange, and expected to turn when leaning to the side, as this participant describes: "…would like the swopper to match the carving motion from skateboarding, bicycle, etc. I really wanted to be able to roll sideways and rotate, with actual rotation should achieve drift effect."

Other participants expressed their frustration with staying balanced on the chair and maintaining their position. The limitation of the base chair height seemed to be a problem for shorter users, as one participant noted: "Should have a shorter Swopper or footrest for short people. It was hard to control because I was on my toes."

Possibly connected to this idea, a few participants in particular indicated that the physical resistance of the chair was a problem, with one participant commenting: "I'd like less resistance for the chair… although maybe my core isn't strong enough. It was harder to control because of that, felt like it took more energy."

One of the most common complaints was related to how the user oriented themselves to the TrackIR mounted behind, as this participant explained: "You should have something to orient the chair for when the user sits down, it's very easy to sit on it incorrectly."

Immersive Experience

As seen in the ratings of immersion, the HMD and NaviChair were rated significantly higher than the screen and joystick. One participant, who was in the HMD group, described the NaviChair as: "… it's more dynamic. Feels like body moving in the space… but would be nice to have some feedback (vibration/shaking) when hitting walls objects."

Interface Preference

When asked about a design review scenario where they could evaluate an architectural design project that they would have some stake in, 40.6% of participants favored the HMD and NaviChair, 37.5% preferred the HMD and joystick, 12.5% chose the 3D projection screen and joystick, and 9.4% desired the 3D projection screen and NaviChair.

3.3.3. Discussion

Several key findings resulted from our study of our IVR representation interface. Regarding spatial orientation performance, no significant differences between the NaviChair and the more familiar joystick interface were found, indicating that orientation performance is comparable between the two locomotion interfaces. Kitson et al., (2015) conducted a similar study with the NaviChair and also did not find that orientation performance was improved with the interface. This stands in contrast to the findings of Grechkin & Riecke (2014), who found that physical rotations benefit only men in a similar orientation task, although full 360° rotations were supported in their study. However, we did find that the HMD was better than the projection screen in orientation performance. In other words, the visual display interface was a significant factor, meaning that user orientation in a virtual building environment is moderately better for combinations of either a joystick or NaviChair when paired with the HMD. This lack of a significant orientation measure effect for locomotion interfaces may be due to an insufficient sample size or problems with the design of the NaviChair, as previous research supports this notion (Ruddle, 2013).

Results also indicate that the HMD causes greater frequency and intensity of motion sickness for users, which in our informal experience has been the case as well. Previous research also provides strong support to the notion that projection screens induce less motion sickness when compared to head-mounted displays (Sharples et al., 2008).

Ratings of locomotion interface controllability were found to be better for the joystick than for the NaviChair. This is not completely surprising, given that users had no previous experience with the NaviChair, and all but one participant had previous experience with a joystick. The majority of these participants indicated that they had previously used joysticks frequently in gaming and leisure activities and were quite familiar with their control. In fact, a number of participants commented that with more practice they believed that they could control the NaviChair as well as the joystick. Findings by Beckhaus et. al., (2005) support this idea, as their informal user study found that their ChairIO interface, which the NaviChair is based upon, was rated as being mostly controllable and intuitive when used for user navigation.

A reverse trend was found for immersion ratings. Participants rated their immersion with the NaviChair as significantly higher, supporting the notion that the embodied control of locomotion provided by the NaviChair can improve immersion and the virtual reality experience. Also, when used with the HMD, the NaviChair was found to significantly improve user's ratings of immersion, indicating the combination of the two can enhance the immersive experience when compared with other locomotion and visual display interface pairings. This coincides with what Marchal et al. (2011) found regarding their leaning locomotion interface (the Joyman), which was rated as more immersive than a traditional joystick. The Chair IO leaning locomotion interface was not previously evaluated for immersion by Beckhaus et al. (2005).

In the context of an architectural design review scenario, users heavily favored the HMD, with roughly half of the users preferring the NaviChair to the joystick for each visual display condition. However, the preference for the HMD in comparison to the more common 3D projection screen may be due to the novelty of the system, as was directly suggested by some participants. Also, the nature of the task was closer to an individual scenario, where communication between users is not necessary. In a multiple user scenario, a shared projection screen display would allow for communication between users.

3.4. Conclusion

As a hands free and embodied locomotion interface for use in architectural practice, we designed the NaviChair locomotion interface to respond to the scenarios and requirements that were outlined in the first phase of the project. Whether usage fits into the realm of process or presentation, or is intended for use by individuals or multiple users, the NaviChair interface offers great potential as an IVR system for architectural design practice.

In relation to the requirements that we outlined for the interface, we found that while the NaviChair was rated as more immersive, it was rated as worse than the joystick in terms of controllability and intuitiveness. In terms of our requirement of low motion sickness risk, the HMD was found to be of greater risk. For our requirement of orientation and navigation performance, our embodied locomotion interface did not perform better than the joystick. Interestingly, the HMD was found to be significantly improve orientation ratings.

In general, users commented on how the NaviChair was a fun and attractive locomotion interface, and with more practice it can potentially grant a similar level of controllability as the joystick. This notion is supported by the findings of user study done by Beckhaus et. al., (2005) for their ChairIO locomotion interface. The main advantage with the NaviChair appears to lie in the enhanced sense of immersion, specifically when used with the HMD. Still, the appropriateness of the display depends on the type of scenario, as multi-user scenarios work best with a shared visual display like a projection screen.

Beyond our findings on the current design of the NaviChair interface, participant interviews also yielded ideas for future development and improvement of the chair. One major issue with the current NaviChair design involves the minimum height setting for the chair. Unfortunately, users under a certain height encountered difficulty in regards to comfortable movement of the seat to a desired position. Because maximum control of the chair depends on the ability to leverage force from the legs and feet, the lack of a solid footing makes the chair much harder to control. This lack of control may also be influenced by the weight of users, with lighter users having insufficient weight to move tilt the chair effectively. Reducing the lowest possible height setting of the chair would solve this issue, allowing shorter and lighter users to comfortably control the interface more easily.

Many users made comments about the sensitivity of the NaviChair motion model and preferred increased or decreased rotation and position translation rates. This problem may be solved by adjustments to the transfer function of the NaviChair. Alternatively, the addition of a saveable sensitivity adjustment would allow users to fine tune the sensitivity of the chair. Ideally, this feature should be saveable so users can enable their preferred settings if they're changed.

The form of the original seat also presented problems for some users, as its simple convex form lacks directionality and can create a sense of instability. A number of participants, especially shorter users, commented on this feeling of instability. This is particularly true when using the HMD, as simply the lack of visual cues from the real environment can result in an unstable feeling for some users. Following the study, we replaced the seat with a concave seat with a middle mounted directional cue similar to a short saddle horn, which according to informal feedback resulted in a more stable experience that intuitively directed the user forward. Alternatively, a tilting chair with a backrest would help to alleviate the problem.

When comparing the 3D projection screen to the HMD, some users discussed the appeal of active head tracking in terms of immersion, and the lack of screen's support for looking up or down in the environment. The addition of an adaptive view frustum would greatly improve a single user's experience when using a projection screen, as we received comments on the lack of responsiveness to head movement for the screen in comparison to the HMD

Lastly, when using the HMD with the NaviChair, many users commented on the sense of nausea they experienced while turning. The current use of the TrackIR system limits rotational tracking of the chair to 30°, which works quite well for a flat screen placed in front of the user, but not as well for visual displays that surround the user or HMDs. For these cases, users were interested in full 360 degree rotational tracking. This would involve simply rotating the chair to the angle the user wants to face and the virtual orientation would change to face that angle. Simply put this would be a 1:1 rotation model, rather than a rate control model.

These possible directions for future development of the NaviChair offer great potential for the improved usability and performance for the interface. Along with rapidly improving visual display interfaces, whether used in process or presentation work, or with individual users or multiple users, Immersive Virtual Reality promises to help redefine the way architecture is designed. We are just beginning to see the future of these interfaces in practice, and there are many exciting areas to explore as we move forward.

Chapter 4. General Discussion

With recent developments in Immersive Virtual Reality technology (IVR), high quality, affordable interfaces are becoming increasingly available. As a design tool, IVR representations could greatly benefit architectural practices in a number of usage scenarios that involve understanding and experiencing space as it would appear in reality. In this thesis we first explored potential usage scenarios and system requirements of an IVR representation interface, then designed a basic IVR representation interface that can be expanded to include each of the usage scenarios we found, and finally tested the interface according to the system requirements outlined previously.

4.1. Summary of Results

4.1.1. Exploration of IVR in Practice

Through our interviews and focus groups we found that architects are greatly interested in using an IVR representation interface in their practice, and they described a broad array of usage scenarios where such an interface would be useful. We also outlined the system requirements of these scenarios, and found that the requirements of an IVR interface for architectural design could be defined according to two dimensions: 1) if the interfaces are intended for single or multiple users, and 2) if the interfaces are intended for use within the architectural design, or for presentation to stakeholders or the public.

4.1.2. Prototype Design

From this, we designed a basic IVR representation interface useful for each of the aforementioned usage scenarios. Components were outlined as the visual display, locomotion interface, and BIM/3D model conversion process, with requirements focusing on offering hands free interface interaction, minimizing motion sickness, and maximizing sensory immersion, controllability, learnability, affordability, ease of set up, and user orientation/navigation abilities.

To allow for flexibility between individual and multiple user scenarios, we designed the system to include either an immersive HMD (Oculus Rift) or a 3D projection screen (Benq W1080ST). Embodied user locomotion is provided by a modified NaviChair interface with a TrackIR 4 system providing system input. The BIM/3D model conversion process involves transferring files into Unity3D using 3dsMax via the .fbx format.

4.1.3. Interface Evaluation

To assess the interface for mainly usability requirements, we tested 32 participants using a balanced mixed factorial design on a spatial orientation task within a virtual 3D model of the proposed Student Union Building for Simon Fraser University. Participants used either the 3D projection screen or Oculus Rift HMD, but were given a chance to try both visual displays. All participants completed the task with both the joystick and the NaviChair for locomotion. Following the experiment, users were asked to answer a number of usability questions.

While we found no significant differences in user orientation ability between the locomotion interfaces, we did find that the HMD users performed significantly better than 3D projection screen users. Also, users rated the immersion as significantly higher for the HMD and NaviChair interface combination. However, interface controllability was rated as lower for the NaviChair, although this is not surprising given that almost all participants had previous experience with a joystick for controlling locomotion and none had experience using the NaviChair previously. These findings are consistent with the findings of Kitson et al., (2015), who found that the NaviChair was rated as significantly more immersive than the joystick, less controllable, and was not significantly different from the joystick in terms of spatial orientation measures. These results conflict with research done by Grechkin & Riecke (2014), who found that physical rotations benefit men and not women in terms of spatial orientation performance. However, in their study, full 360° rotation was supported, which the current version of the NaviChair does not support.

For a promotional simulation or occupant testing scenario 78% of students favored the HMD over the projection screen (40.6% favored HMD and NaviChair). This may have been due to the novelty of using the HMD, or perhaps was due to the higher ratings of immersion of the system compared with other interface pairings. Interestingly, our conversations with architects resulted in their agreement that the projection screen would be preferable, as it allows multiple users to view, reference, and communicate through the display.

Relating back to the requirements we initially outlined for our system in Chapter 2, we were surprised by the fact that the NaviChair does not grant high controllability in comparison to the joystick, but that it does offer greater potential for sensory immersion. Regarding our requirement of low motion sickness risk, the HMD had a significantly greater risk compared to the 3D projection screen, although also had greater potential for sensory immersion. However, this finding of an HMD increasing the risk of motion sickness has been shown to be an issue in previous research (Sharples et al., 2008). In comparison to the work of Beckhaus et al. (2007), we found that about half of the users struggled with learning and using the NaviChair and preferred the joystick in terms of controllability. In contrast, their findings indicated that users learned the system quickly and easily and could perform complex tasks after a short time. This could possibly be due to the lack of a joystick comparison condition, the use of different task environments, or perhaps differences in our motion model and theirs contributed to their different findings.

4.2. Limitations

Several limitations apply to each component of our research. First, our interviews consisted of only seven architects and only two focus groups. It is possible that with more interviews and focus groups we might discover more scenarios and more informative feedback regarding the use of IVR in architectural practice. Also, our investigation of architects involved asking only what types of scenarios would be of interest. While this is a good starting point when thinking about the design of a system, it is unknown how useful any of these usage scenarios might actually be in practice. Furthermore, the validity of our requirements is also lessened as they were informed based only on interviews and focus groups. Only when real world testing in each of the scenarios is completed can strong statements regarding validity of the scenarios and requirements be made.

Regarding the interface design, limitations of processing power and the size of the model are important to consider. Our conversion process attempts to minimize the impact of these issues, but balancing processing power with the IVR interface and virtual environment is an ongoing struggle.

In terms of the IVR interface evaluation, our conclusions must be limited due to the nature of our participants and task. Because our experiment did not involve actual architects, but only students that could be considered stakeholders in the architectural design of the proposed SFU Student Union Building, our user feedback about preferred interfaces concerns only the usefulness in external presentation, single user scenarios. Also, given the recruitment bias and the low mean ages of participants (M = 23.9), the validity of interface usability for architects is also weakened. However, in our presentations to architects at Perkins + Will, users found the interface to be very usable and quickly learned how to operate it within the virtual environment.

Other limitations of our evaluation concerning the comparison of the joystick with the NaviChair relate to the previous experience each participant had with the joystick in comparison to the NaviChair, which no participant had used previously. This makes comparison more difficult, and perhaps with more experience users would respond differently to the task. Also, because our joystick was limited to only 2DOF, the mapping controls of the joystick were different from the NaviChair, which was 3DOF. It is possible that the added degree of freedom of the NaviChair affected how usable participants found the system, and controllability ratings were lower as a result. Lastly the height of the NaviChair was a concern for shorter users, as the ability to leverage and stabilize themselves using their feet was impeded upon. This may have affected usability ratings.

Unfortunately, participant height was not recorded and this cannot be confirmed. Specifically regarding the orientation task, participants in the evaluation commented on the challenge of the task, and just remember the objects themselves was difficult and was a major focus during the experiment. This may have distracted participants from the location of each object, and may indicate that this task is not suitable for measuring orientation performance. This task was based on a similar orientation task used by Grechkin & Riecke (2014), and was revised for a similar study done by Kitson et al., (2015). This revised version of the orientation task attempted to compensate for the memorization issues by allowing the users to view all object locations from a fixed vantage point, and minimized compounding errors by giving feedback on pointing errors limiting the amount of error allowed to continue the task. However, Kitson et al., (2015) did not find any significant orientation performance differences between the joystick and NaviChair.

4.3. Design Guidelines

Based on user feedback and our own observations, a number of design guidelines can be gleaned from our exploration. These are outlined below.

4.3.1. Minimize Sensory Disconnection

First, many users commented on the sense of motion sickness that was experienced when using the NaviChair with the HMD. This mainly seemed to occur when users were turning, and we hypothesize this is a result of the limitations of the TrackIR system. Because turning was velocity controlled by deviating a specific angle from a central position, visual rotation would still occur in the visual display as users rotated physically in the opposite direction while they returned to the center. One possible solution may be using a sensor that can wirelessly provide 360 rotation data to users would allow users to simply rotate to the desired angle, then lean and travel in that direction, thus minimizing the sensory disconnection associated with motion sickness. However, this issue may simply be caused by a combination of head tracking and rotational tracking on the NaviChair. More investigation into the cause of this problem is needed, as these conflicting sensory cues also occurred during translation and users did not find this to be a major source of discomfort.

4.3.2. Allow Accessibility for All Heights

As we mentioned previously, the height of such a leaning interface can affect usability of the system, and the ability to properly support all user heights should be strongly considered. During user testing, shorter users commented on their struggle to stabilize themselves and leverage their weight while leaning or turning. This may have also been connected to user weight as well, as users that weighed less would have a harder time deflecting the NaviChair and controlling the system. However, by solving the issue of height with the chair, users would be able to compensate for lower weights regardless.

4.3.3. Provide Adjustable Locomotion Sensitivity

Participants in our evaluation often commented on how the NaviChair locomotion interface was either too sensitive or not sensitive enough in different components of locomotion. To compensate for this, the NaviChair should have adjustable settings in which users can tune the transfer function according to their desired rate of rotation or velocity.

4.3.4. Support Multiple Control Mappings

For the NaviChair, mapping of rotation was an issue for some users. Based on our observations, as well as user feedback, some users expected rotation to be controlled by leaning from side to side, much as they would on a bicycle. The rotation of the user was instead controlled by rotating the lower body, and user confusion resulted. A setting which allows users to switch based on their preference and task demands would help solve this problem. In the original works of Beckhaus et al. (2007), multiple mappings were presented for different uses, and allowing the user to switch between these would be ideal.

4.3.5. Give Users a Sense of Safety

Some users commented on how they felt unsafe, commenting that they felt they might fall over, while on the NaviChair, particularly when using the HMD. These findings are consistent with the user study of Beckhaus et al (2005), which found that for some users the Swopper Chair felt unsafe when leaning backwards and balance was an issue when attempting to use both feet. We propose that the convex nature of the NaviChair seat may have contributed to this. Additionally, users sometimes struggled with seating themselves with the TrackIR reflector directly behind them. This caused unwanted rotation of the visual display when users seated themselves incorrectly. Stronger force feedback for rotations may help solve this issue, along with a seat that conveys where the user is facing relative to the TrackIR intuitively. Following the experiment, we redesigned the seat to have a concave, U shaped form that cued users to position themselves with the TrackIR reflector directly behind them and helped users to feel more securely grounded to the chair. Based on informal feedback, this change in seat form made users feel safer and there were fewer problems with incorrect seating of the user relative to the TrackIR reflector.

4.4. Conclusion and Outlook

Our exploration, design, and evaluation of IVR representation interfaces for architectural practice resulted in a number of intriguing contributions to the field of IVR interfaces, as well as specifically on use in architectural practice. First, we outlined a number of scenarios that an IVR representation interface for architectural practice might be useful for. We also classified these scenarios according to two dimensions that influence the requirements associated with each scenario. Additionally, we outlined the requirements for a basic IVR representation interface that can be expanded to include each scenario. We described the design of our system and evaluated it to determine how well it responds to the basic requirements of an IVR representation interface. Our findings indicate that our embodied locomotion interface design is more immersive than a standard joystick, which is of interest to those interested in increasing the sensory immersion of a user in IVR. Lastly, we provided some useful, actionable guidelines for designers of IVR locomotion interfaces and design recommendations for the NaviChair specifically

It is unknown if our findings on the scenarios and requirements of IVR representation interfaces for architectural design are generalizable to the design and development of other IVR interfaces, or if the results and design guidelines regarding our IVR interface are also generalizable to other domains outside architectural design. This remains an open question that warrants further exploration.

We have also raised questions for the future of such systems. How an IVR representation will be used in practice, how our interface would perform in other usage scenarios, how our interface would perform when support for gestural modeling is implemented, and how our current IVR representation interface can be modified to improve controllability, stand as some of the questions raised by this research project. After usability issues are addressed, future research involving our interface can focus on more design practice oriented tasks, such as a case study of a design critique or a comparison of design development between a process that involves a traditional representation and one that involves a process with IVR representations.

Regarding the future of our IVR representation interface, we intend to pursue future usability development and complete fulfillment of our requirements. Beyond this, we are exploring the potential of a more focused design scenario oriented around a design review involving architects within the firm. Possibly over long distances, the NaviChair could help designers to discuss ideas and collaborate through a shared screen. Alternative tilting chairs are also being explored, with the “Muvman” appearing to fulfill our criteria of a backrest and cost better than the Swopper Chair.

Future developments in technology, along with our informed refinements of the design, should result in a powerful design representation tool that architects can use in a wide array of scenarios. With visual displays improving in resolution, tracking system latency limitations improving, and processing power constantly increasing, immersivity and motion sickness issues will likely improve as time goes on. Compared with a traditional joystick, our design of the NaviChair interface provides a more immersive and embodied hands free locomotion interface for use in the scenarios we outlined. Also, as more BIM/3D modeling tools realize the power of IVR design representation interfaces, demand to include these representations in the design process will likely increase.

Indeed, we have only just begun to explore the usefulness of our IVR representation interface. With further development and subsequent deployment in architectural practice, the full potential that IVR can offer to architectural practice will begin to be realized. Once the possibilities of experiencing a space before it is built are finally known, we believe the built environment we experience everyday move one step closer to the highest form of design; that which encompasses our needs, our wants, and our dreams.

References

Abdelmohsen, S. (2012). Genres of communication interfaces in BIM enabled architectural practice (p. 81). Presented at the 6th ASCAAD Conference 2012 CAAD Innovation.

Achten, H. (2000). DDDOOLZ. A Virtual Reality Sketch Tool for Early Design. Retrieved August 1, 2013, from http://cumincad.scix.net.proxy.lib.sfu.ca/cgi-bin/works/Show?_id=eb8a&sort=DEFAULT&search=virtual%20reality&hits=2320

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., & O'Reilly, K. (2011). Technology adoption in the BIM implementation for lean architectural practice. *Automation in Construction*, *20*(2), 189–195. http://doi.org/10.1016/j.autcon.2010.09.016

Arthur, E. J., Hancock, P. A., & Chrysler, S. T. (1993). Spatial Orientation in Real and Virtual Worlds. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *37*(4), 328–332. http://doi.org/10.1177/154193129303700416

Batschelet, E. (1981). *Circular statistics in biology* (Vol. 111). Academic press London.

Beckhaus, S., Blom, K. J., & Haringer, M. (2005). Intuitive, hands-free travel interfaces for virtual environments.

Beckhaus, S., Blom, K. J., & Haringer, M. (2007). ChairIO–the chair-based Interface. *Concepts and Technologies for Pervasive Games: A Reader for Pervasive Gaming Research*, *1*, 231–264.

Boon, J. (2009). Preparing for the BIM Revolution. *Proceedings of 13th Pacific Association of Quantity Surveyors Building the future together: 13th Pacific Association of Quantity Surveyors Congres.*

Bowman, D. A., Koller, D., & Hodges, L. F. (1998). A methodology for the evaluation of travel techniques for immersive virtual environments. *Virtual Reality*, *3*(2), 120–131.

Bowman, D., & McMahan, R. P. (2007). Virtual reality: how much immersion is enough? *Computer*, *40*(7), 36–43.

Bruder, G., Steinicke, F., & Hinrichs, K. H. (2009). Arch-Explore: A natural user interface for immersive architectural walkthroughs (pp. 75–82). Presented at the IEEE Symposium on 3D User Interfaces, 2009. 3DUI 2009. http://doi.org/10.1109/3DUI.2009.4811208

Bullinger, H.-J., Bauer, W., Wenzel, G., & Blach, R. (2010). Towards user centred design (UCD) in architecture based on immersive virtual environments. *Computers in Industry*, *61*(4), 372–379.

Cobb, S. V., Nichols, S., Ramsey, A., & Wilson, J. R. (1999). Virtual reality-induced symptoms and effects (VRISE). *Presence*, *8*(2), 169–186.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*(1), 155.

Dowhower, J. F. (2010). Adapting building information modeling (BIM) for affordable & sustainable housing (Master's thesis). https://repositories.lib.utexas.edu/bitstream/handle/2152/ETD-UT-2010-05-1391/DOWHOWER-THESIS.pdf.txt?sequence=5

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. John Wiley & Sons.

Ermi, L., & Mäyrä, F. (2005). Fundamental components of the gameplay experience: Analysing immersion. *Worlds in Play: International Perspectives on Digital Games Research*, *37*.

Fuchs, P., Moreau, G., & Guitton, P. (Eds.). (2011). *Virtual Reality: Concepts and Technologies*. CRC Press.

Gaunet, F., & others. (1998). Virtual environments as a promising tool for investigating human spatial cognition. *Cahiers de Psychologie Cognitive/Current Psychology of Cognition*.

Goldschmidt, G., & Porter, W. L. (2004). *Design Representation*. London: Springer Verlag. Retrieved from http://www.springer.com/engineering/mechanical+engineering/book/978-1-85233-753-7

Grant, S. C., & Magee, L. E. (1998). Contributions of proprioception to navigation in virtual environments. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *40*(3), 489–497.

Grechkin, T. Y., & Riecke, B. E. (2014). Re-evaluating Benefits of Body-based Rotational Cues for Maintaining Orientation in Virtual Environments: Men Benefit from Real Rotations, Women Don'T. In *Proceedings of the ACM Symposium on Applied Perception* (pp. 99–102). New York, NY, USA: ACM. http://doi.org/10.1145/2628257.2628275

Greenwood, D., Horne, M., Thompson, E. M., Allwood, C. M., Wernemyr, C., & Westerdahl, B. (2008). Strategic Perspectives on the Use of Virtual Reality within the Building Industries of Four Countries. *Architectural Engineering and Design Management*, *4*(2), 85–98. http://doi.org/10.3763/aedm.2008.0076

Gresty, M. A., Waters, S., Bray, A., Bunday, K., & Golding, J. F. (2003). Impairment of spatial cognitive function with preservation of verbal performance during spatial disorientation. *Current Biology*, *13*(21), R829–R830.

Gu, N., & London, K. (2010). Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, *19*(8), 988–999.

Harris, L. R., Jenkin, M., Zikovitz, D., Redlick, F., Jaekl, P., Jasiobedzka, U., … Allison, R. S. (2002). Simulating self-motion I: Cues for the perception of motion. *Virtual Reality*, *6*(2), 75–85.

Heeter, C. (1992). Being there: The subjective experience of presence. *Presence: Teleoperators and Virtual Environments*, *1*(2), 262–271.

Henry, D., & Furness, T. (1993). Spatial perception in virtual environments: Evaluating an architectural application (pp. 33–40). Presented at the , 1993 IEEE Virtual Reality Annual International Symposium, 1993. http://doi.org/10.1109/VRAIS.1993.380801

Jota, R., Araújo, B. R. de, Bruno, L. C., Pereira, J. M., & Jorge, J. A. (2010). IMMIView: a multi-user solution for design review in real-time. *Journal of Real-Time Image Processing*, *5*(2), 91–107. http://doi.org/10.1007/s11554-009-0141-1

Kitson, A., Riecke, B., Hashemian, A., & Neustaedter, C. (2015). NaviChair: Evaluating an Embodied Interface Using a Pointing Task to Navigate Virtual Reality. Presented at the Spatial User Interaction, Los Angeles, CA, USA: ACM.

Klatzky, R. L., Loomis, J. M., Beall, A. C., Chance, S. S., & Golledge, R. G. (1998). Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. *Psychological Science*, *9*(4), 293–298.

Kruijff, E., Riecke, B., Trekowski, C., & Kitson, A. (2015). Upper Body Leaning can affect Forward Self-Motion Perception in Virtual Environments. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction* (pp. 103–112). ACM.

Lombard, M., & Ditton, T. (1997). At the heart of it all: The concept of presence. *Journal of Computer-Mediated Communication* , *3*(2), 0-0.

Marchal, M., Pettre, J., & Lecuyer, A. (2011). Joyman: A human-scale joystick for navigating in virtual worlds. In *Proceedings of the 2011 IEEE Symposium on 3D User*

Interfaces (pp. 19–26). Washington, DC, USA: IEEE Computer Society. Retrieved from http://dl.acm.org.proxy.lib.sfu.ca/citation.cfm?id=2013881.2014206

May, M., & Klatzky, R. L. (2000). Path integration while ignoring irrelevant movement. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(1), 169.

Merriam, S. B. (2002). *Qualitative research in practice: Examples for discussion and analysis*. Jossey-Bass Inc Pub.

Mobach, M. P. (2008). Do virtual worlds create better real worlds? *Virtual Reality*, *12*(3), 163–179. http://doi.org/10.1007/s10055-008-0081-2

Nielsen, J. (1994). *Usability engineering*. Elsevier.

Pressman, A. (2006). Computers and Practice : The Digital Guerrilla. In *Professional practice 101: business strategies and case studies in architecture* (2nd ed., pp. 285–288). Hoboken, New Jersey: Wiley.

Reason, J. (1978). Motion sickness adaptation: a neural mismatch model. *Journal of the Royal Society of Medicine*, *71*(11), 819.

Riecke, B. E. (2010). *Compelling Self-Motion Through Virtual Environments Without Actual Self-Motion-Using Self-Motion Illusions ('Vection') to Improve VR User Experience*. INTECH Open Access Publisher.

Riecke, B. E., Cunningham, D. W., & Bülthoff, H. H. (2007). Spatial updating in virtual reality: the sufficiency of visual information. *Psychological Research*, *71*(3), 298–313.

Riecke, B. E., Heyde, M. V. D., & Bülthoff, H. H. (2005). Visual cues can be sufficient for triggering automatic, reflexlike spatial updating. *ACM Transactions on Applied Perception (TAP)*, *2*(3), 183–215.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*(6), 1157.

Riva, G., Mantovani, F., Capideville, C. S., Preziosa, A., Morganti, F., Villani, D., … Alcañiz, M. (2007). Affective interactions using virtual reality: the link between presence and emotions. *Cyberpsychology & Behavior: The Impact of the Internet, Multimedia and Virtual Reality on Behavior and Society*, *10*(1), 45–56. http://doi.org/10.1089/cpb.2006.9993

Ruddle, R. A. (2013). The Effect of Translational and Rotational Body-Based Information on Navigation. In F. Steinicke, Y. Visell, J. Campos, & A. Lécuyer (Eds.), *Human Walking in Virtual Environments* (pp. 99–112). New York, NY: Springer New York. Retrieved from http://link.springer.com/10.1007/978-1-4419-8432-6_5

Schubert, T., Friedmann, F., & Regenbrecht, H. (n.d.). Decomposing the sense of presence: Factor analytic insights.

Schuemie, M. J., Van Der Straaten, P., Krijn, M., & Van Der Mast, C. A. (2001). Research on presence in virtual reality: A survey. *CyberPsychology & Behavior*, *4*(2), 183–201.

Sharples, S., Cobb, S., Moody, A., & Wilson, J. R. (2008). Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems. *Displays*, *29*(2), 58–69.

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

Stamps, A. E. (1994). All Buildings Great and Small Design Review From High Rise to Houses. *Environment and Behavior*, *26*(3), 402–420. http://doi.org/10.1177/001391659402600306

Steinicke, F., Bruder, G., Hinrichs, K., Lappe, M., Ries, B., & Interrante, V. (2009). Transitional Environments Enhance Distance Perception in Immersive Virtual Reality Systems (pp. 19–26). New York, NY, USA: ACM. http://doi.org/10.1145/1620993.1620998

Unger, R., & Chandler, C. (2012). *A Project Guide to UX Design: For user experience designers in the field or in the making*. New Riders.

van Dam, A., Laidlaw, D. H., & Simpson, R. M. (2002). Experiments in Immersive Virtual Reality for Scientific Visualization. *Computers & Graphics*, *26*(4), 535–555. http://doi.org/10.1016/S0097-8493(02)00113-9

Vidyarthi, J. (2014). Brainsketching: Collaborative Interaction Design. *User Experience Magazine*, *14*(1).

Visser, W. (2006). Designing as Construction of Representations: A Dynamic Viewpoint in Cognitive Design Research. *Human–Computer Interaction*, *21*(1), 103–152. http://doi.org/10.1207/s15327051hci2101_4

Visser, W. (2009). Design: one, but in different forms. *Design Studies*, *30*(3), 187–223. http://doi.org/10.1016/j.destud.2008.11.004

Visser, W. (2010). Visser: Design as construction of representations. *Collection*, (2), 29–43.

Wang, R. F., & Spelke, E. S. (2000). Updating egocentric representations in human navigation. *Cognition*, *77*(3), 215–250.

Wan, X. I., Wang, R. F., & Crowell, J. A. (2009). Spatial updating in superimposed real and virtual environments. *Attention, Perception & Psychophysics*, *71*(1), 42–51. http://doi.org/10.3758/APP.71.1.42

Ware, C., & Franck, G. (1996). Evaluating Stereo and Motion Cues for Visualizing Information Nets in Three Dimensions. *ACM Trans. Graph.*, *15*(2), 121–140. http://doi.org/10.1145/234972.234975

Wasserman, B., Sullivan, P., & Palermo, G. (2000). *Ethics and the Practice of Architecture*. John Wiley & Sons.

Webster, A., Feiner, S., MacIntyre, B., Massie, W., & Krueger, T. (1996). Augmented reality in architectural construction, inspection and renovation (pp. 913–919).

Wiegers, K., & Beatty, J. (2013). *Software requirements*. Pearson Education.

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

Wojtowicz, J., & Butelski, K. (1999). Lessons from distributed design practice. In conference proceedings of eCAADe.

Yaneva, A. (2005). Scaling Up and Down Extraction Trials in Architectural Design. *Social Studies of Science*, *35*(6), 867–894.

Yifan, L. (2014). *Workflow of Exporting Revit Models to Unity*. Pennsylvania State University Computer Integrated Construction Group. Retrieved from https://bim.wikispaces.com/file/view/Revit_3DS_Unity%20Workflow.pdf/511568080/Revit_3DS_Unity%20Workflow.pdf

Yi, X., Qin, S., & Kang, J. (2009). Generating 3D architectural models based on hand motion and gesture. *Computers in Industry*, *60*(9), 677–685.

Appendix A.1

Interview Research Study: Informed Consent Form

School of interactive Arts + Technology, Simon Fraser University Surrey
250 – 13450 102 Avenue, Surrey, BC V3T 0A3 Canada
Tel: +1 778.782.7474

Informed Consent by Participants in an Interview Research Study

Study title: Architectural Design Representations and Virtual Reality Experience
Investigator: Jacob Freiberg

What you will be asked to do?

You will be asked a series of questions pertaining to architectural practice, design representations, and design process and presentation. A demonstration of the Oculus Rift will be included in the interview, and following the interview a short tour of the office will take place.

Benefits of the study:

You can obtain results from this study, once completed, by contacting the principal investigator by email at [redacted] or by phone at [redacted]

Possible Risks:

Some people experience motion sickness while using Virtual Reality displays. If you have a history of motion sickness, please inform the interviewer. If you feel sick, or uncomfortable at any time during the demonstration you should alert the interviewer and they will end the demonstration.

Any information that is obtained during this study will be kept confidential to the extent permitted by the law. Data will be retained at least for the duration of the project, and will be stored in secure locations like locked rooms and/or on password-secured storage devices. In cases where audio/video recording is used, this will only be done with the participants' consent. Knowledge of your identity is not required. You will not be required to write your name or any other identifying information on research materials (other than this consent form).

Your signature on this form will signify that you have received a document that describes the procedures, possible risks, and benefits of this research study; that your are at least 19 years old; that you have received an adequate opportunity to consider the information describing the study and that you voluntarily agree to participate in the study.

The University and those conducting this research study subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort, and safety of participants. This research is being conducted under permission of the Simon Fraser Research Ethics Board. The chief concern of the Board is for the health, safety, and psychological well being of research participants. Should you wish to obtain information about your rights as a participant in research, or about the responsibilities of researchers, or if you have any questions, concerns, or complaints about the manner in which you were treated in this study, please contact the Director, Office of Research Ethics by email at [redacted] or phone at [redacted]

I understand that I may withdraw my participation at any time without penalties. I also understand that I may register any complaint with the Director of the Office of Research Ethics or the researcher(s) named above or with the Director of School of Interactive Arts + Technology. I have been informed that the research will be confidential. I understand the risks and contributions of my participation in this study and agree to participate:

Participant first name:_______________________ Participant last Name:______________________________
Participant Contact information (email/phone):

Date:____________________ Participant Signature:____

Appendix A.2

Interview Research Study: Questions and Guide

November 21, 2013

<u>Interview Outline</u>

Research Questions:
R1) How do 3D digital models currently facilitate exploration and iteration during the architectural design process?

R2) How do architects assess the spatial qualities and experience of a space using design representations?

R3) How does the type of practice affect design representation tools?

R4) How can Virtual Reality design representations improve an architect's design process?

Research Topics: Virtual Reality, Architectural Design Tools, Architectural Design Representation, Architectural Design Process

Pre Interview Structure:
P1) Introduce: I am interested in understanding how architects conceive of spatial design, and I would like to build digital design tools that support new ways of visualizing spatial planning.

P2) Find comfortable location for interview (fairly private)

P3) Signing ethics forms

P4) Their name, position, firm, how long they have been practicing, educational and professional background.

Main Interview Structure:
Q1) How do you think architectural practice has changed over the course of your career?

Q2) Describe what design tool technologies you think architects will be using in 20 years?

<u>Type of Practice:</u>
Q3) How are your current/recent projects organized in time, internal personnel, and external personnel?

Q4) Describe what you see as the strengths and weaknesses of this temporal-organizational structure.

<u>Process:</u>
Q5) What path does design process take in your practice? (scale, representation, transitioning, tools, collaboration, etc)

Q6) What are common problems you encounter with your design process representations?

Q7) How do you usually assess how the designed space will appear visually for future occupants? (imagine, conceptual, view screen, model, etc)

Q8) How do you assess how the designed space will be experienced, or "feel"? (imagine, conceptual, view screen, model, etc)

Q9) Do you draw/render first person perspectives? At what point in the process?

Q10) If comparing alternatives, do you use design representation tools to determine which is better – how? What criteria do you use?

Q11) How frequently do you transition between different design mediums? (reference example)

Q12) Do you attempt to use your process representations as your presentation representations – describe?

Presentation:
Q13) Describe the clientele your practice usually attracts.

Q14) How do clients respond to your/your team's design representations during review sessions?

Q15) What kinds of problems can be encountered during the presentation?

Transition into demo: As I mentioned in the beginning I'm interested in… etc etc… I'd like to show you … Imagine the future while you're trying this…
----- Give Oculus Demo

Virtual Reality:
Q16) In the future, do you think an immersive HMD experience could be useful in your design process?

Q17) Do you think this technology would be useful in client presentation situations?

Q18) If you were to incorporate this into your practice, what do you think the strengths and weaknesses of this tool would be?

Q19) Does your firm use touch surfaces for design or review, have they in the past, or do they plan to in the future?

End) Thank you, in my own research I think this technology presents great potential and am currently working on a design representation tool – I have early ideas but would like your help with the design. (tell them about the tool and gauge their interest in partnering) (give them a little packet and tell them about the moneys)

Tour
QT1) Can we go on a tour of the office?

Appendix B.1

Focus Group Research Study: Informed Consent

School of interactive Arts + Technology, Simon Fraser University Surrey
250 – 13450 102 Avenue, Surrey, BC V3T 0A3 Canada
Tel: +1 778.782.7474
Application Number: 2014s0344

Informed Consent by Participants in a Focus Group Research Study

Study title: An Immersive Virtual Reality Interface for Architectural Practice

Investigator: Jacob Freiberg

Introduction:

Immersive Virtual Reality is quickly emerging as a new form of architectural design representation. We are interested in learning more about the possibilities that an Immersive Virtual Reality tool would offer architectural practice and how such a tool should be designed.

What you will be asked to do?

We request that you participate in a focus group in which you will be asked to discuss a series of questions pertaining to architectural practice, design representations, design process and presentation, and immersive virtual reality. An optional demonstration of the Oculus Rift will be included after the focus group, and you will be asked to participate in a creative exercise on the design of an immersive virtual reality workstation.

Benefits of the study:

Your responses, ideas, and feedback will inform research on immersive virtual reality workstations for use in architectural practice. You can obtain results from this study, once completed, by contacting the principal investigator by email at [redacted] or by phone at [redacted]

Possible Risks:

Some people experience motion sickness while using Virtual Reality displays. If you have a history of motion sickness, please inform the moderator. If you feel sick or uncomfortable at any time during the demonstration you should alert the moderator.

Participants will be able to identify each other and hear each other's response during the study as they will participate together as a group. This will breach participant anonymity and confidentiality of data, and you may choose not to participate in the study at any time.

Although your identity will be known by those also participating in the study, any information that is obtained during this study will be kept confidential to the extent permitted by the law. Data will be retained at least for the duration of the project, and will be stored in secure locations like locked rooms and/or on password-secured storage devices. In cases where audio/video recording is used, this will only be done with the participants' consent. Names will be removed and replaced with non-specific identifiers. Transcriptions will be stored on a password protected sfu server.

Your signature on this form will signify that you have received a document that describes the procedures, possible risks, and benefits of this research study; that your are at least 19 years old; that you have received an adequate opportunity to consider the information describing the study and that you voluntarily agree to participate in the study.

Remuneration:

Participants may be remunerated with a selection of chocolate and sweets during the focus group. No peanuts will be involved in the production of any of the candies.

The University and those conducting this research study subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort, and safety of participants. This research is being conducted under permission of the Simon Fraser Research Ethics Board and the offices of Perkins & Will. The chief concern of the Board is for the health, safety, and psychological well-being of research participants. Should you wish to obtain information about your rights as a participant in research, or about the responsibilities of researchers, or if you have any questions, concerns, or complaints about the manner in which you were treated in this study, please contact the Office of Research Ethics Director, Dr. Jeff Toward, by email at [redacted] or by phone at [redacted]. Questions on the study should be directed towards Jacob Freiberg via email at [redacted] or by phone at [redacted].

I understand that I may withdraw my participation at any time without penalties. I also understand that I may register any complaint with the Director of the Office of Research Ethics or the researcher(s) named above or with the Director of School of Interactive Arts + Technology. I have been informed that the research will be confidential. I understand the risks and contributions of my participation in this study and agree to participate:

Do you agree to be video/audio-taped? YES ___ NO ___

Participant first name:_______________________ Participant last name:_____________________________

Date:___________________ Participant Signature:____

Appendix B.2

Focus Group Research Study: Questions and Guide

July 15, 2014

Focus Group Outline

i) General Format and Background Information (10 min)

1. Tell moderator's background and name
    a. Explain goals of research
        i. Affordable IVR system for Arch Practice
    b. Thanks!
2. Explain informed consent
    a. Explain privacy issues (won't share the video/personal info)
    b. Explain data collection and use
3. Explain focus group format
    a. Explain free discussion format
    b. Explain overall plan:
        i. Questions & Discussions (conversation on your design process)
        ii. Overview of VR (to give context on the design of a IVR system)
        iii. Questions & Discussions (conversation on scenarios IVR would be useful)
        iv. Activity (to "tease out your approaches")
        v. Our current ideas on the interface
        vi. Requirements questionnaire
        vii. Activity (to generate ideas on how our interface could work in a system)
4. Ask participant's backgrounds and names
    a. Record names on name cards (markers)
    b. Ask professional background (1 minute per person)

ii) Questions and Discussion pt. 1 (20 min)

1. Can you outline a typical design process you use for your projects?
    a. Scale
    b. Representations
    c. Transitioning
    d. Tools
    e. Collaboration
    f. Review
2. Can you talk a bit about the pros and cons of the computer aided design tools you use?
    a. Compare to other representations
    b. Navigation Interfaces
        i. Viewpoint positioning
        ii. Learnability
        iii. Other problems
    c. 3D displays

iii) Introduction to Immersive Virtual Reality (5 min)

1. Brief Introduction to Immersive Virtual Reality
    a. Defining Immersive Virtual Reality
        i. Immersion
        ii. Sensory feedback
        iii. Visual displays
        iv. Interaction
        v. Locomotion

1

iv) Questions and Discussion pt 2 (15 min)

1. Imagine you are working on your current project. How would you use a more Immersive Virtual Reality workstation in your design process?
   (2 minute individual written responses with names, more time?, then discuss)
   a. Scenarios
      i. Sketch modeling
      ii. 3D data visualization
      iii. Experiential and spatial assessment
      iv. Internal review session
      v. Collaboration
      vi. Conflict detection
   b. Internal/External use
   c. Frequency/Duration of use
2. What are the most promising tasks/scenarios? (rank on board and photograph)

v) System design activity pt 1 (10 min)

1. Explain the brainsketching protocol
   (2 min to draw ideas, then pass left, work for 1 min, pass left again, continue)
2. Based on the most popular task/scenario, design your dream interface.
   a. Locomotion
   b. 3D displays
   c. Immersion
   d. Absolute vs relative positioning
   e. Other?
3. Discuss as a group – <u>"Why" is the most important</u>

vi) Current system design and discussion (5 min)

1. Explain that ideas are open to critique - early in the design process.
2. Swopper Chair
   a. Demo
   b. Usability
   c. Usefulness
   d. Displays

*(**5 minute break**)*

vii) Requirements Questionnaire (10 min)

1. Pass out questionnaire
2. Discuss and rank the requirements (photo of board)

viii) System design activity pt 2 (10 min)

1. Using the Swopper chair for user locomotion, design your dream interface.
   a. Locomotion
   b. 3D displays
   c. Immersion
   d. Absolute vs relative positioning
   e. Other?
2. Discuss as a group – <u>"Why" is the most important</u>

Appendix B.3

Focus Group Research Study: Requirements Questionnaire

Please rate how important the following system features are for an Immersive Virtual Reality Interface in Architectural Practice:

The interface should have a 3D (stereoscopic) display.

1 2 3 4 5 6 7 8 9 10

(Strongly disagree) (I don't know) (Strongly agree)

The visual display should be viewable by multiple users at the same time.

1 2 3 4 5 6 7 8 9 10

(Strongly disagree) (I don't know) (Strongly agree)

I would like to be seated while using the interface.

1 2 3 4 5 6 7 8 9 10

(Strongly disagree) (I don't know) (Strongly agree)

The interface should allow hands free locomotion.

1 2 3 4 5 6 7 8 9 10

(Strongly disagree) (I don't know) (Strongly agree)

The visual display should hide the real world from view.

1 2 3 4 5 6 7 8 9 10

(Strongly disagree) (I don't know) (Strongly agree)

The interface should fit within a 3 m x 3 m area.

1 2 3 4 5 6 7 8 9 10

(Strongly disagree) (I don't know) (Strongly agree)

Appendix C.1

Experimental Evaluation: Informed Consent Form

School of Interactive Arts + Technology (SIAT), Simon Fraser University Surrey
250 -13450 102 Avenue, Surrey, BC V3T 0A3 Canada
Tel: +1 778.782.7474 Fax: +1 778.782.7478 Web: http://www.surrey.sfu.ca

SIMON FRASER UNIVERSITY
Informed Consent by Participants in an Experimental Research Study

Study Title: Locomotion, Navigation, and Orientation in Immersive Virtual Environments
Investigator's Name: Jacob Freiberg

Any information that is obtained during this study will be kept confidential to the extent permitted by the law. Data will be retained at least for the duration of the project, and will be stored in secure locations like locked rooms and/or on password-secured storage devices. In cases where audio/video recording is used, this will only be done with the participants' consent. Knowledge of your identity is not required. You will not be required to write your name or any other identifying information on research materials.

Your signature on this form will signify that you have received a document that describes the procedures, possible risks, and benefits of this research study; that your are at least 19 years old; that you have received an adequate opportunity to consider the information in the documents describing the study – this information document will depend on the specific study you will be participating in; and that you voluntarily agree to participate in the study.

The University and those conducting this research study subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort, and safety of participants. This research is being conducted under permission of the Simon Fraser Research Ethics Board (REB #2012c0022). The chief concern of the Board is for the health, safety, and psychological well being of research participants. Should you wish to obtain information about your rights as a participant in research, or about the responsibilities of researchers, or if you have any questions, concerns, or complaints about the manner in which you were treated in this study, please contact the Director, Office of Research Ethics Dr. Jeff Toward, by email at [redacted] or by phone at [redacted]. Questions on the study should be directed to the investigator listed below.

Title: Locomotion, Navigation, and Orientation in Immersive Virtual Environments
Investigator Name: Jacob Freiberg
Email of investigator (where you can obtain research results once the study is finished): [redacted]
Investigator Department: School of Interactive Arts and Technology (SIAT), http://www.siat.sfu.ca/

Below is a description of what you will be asked to do in this study. Please do not hesitate to ask if anything should remain unclear:

Purpose and potential benefits of this study

This study will help us to understand how people perceive the space around them in virtual environments. The results will contribute to the development of better theories about how the brain works. In addition, the study will aid in the design of improved virtual reality interfaces, which can be used in research, training, and entertainment. You can obtain results from this study, once completed, by contacting the principal investigator by email at [redacted] or by phone at [redacted]

What you will be asked to do

In this study you will be asked to navigate through a virtual building environment using different visual display and locomotion interfaces. During different phases of the experiment you will control your movement using either a joystick interface or a tilting swivel chair interface, and you will view the environment on either a head-mounted display or a stereoscopic projection screen.

The experiment itself will consist of two main experiment trials, each of which will be preceded by a short practice trial. At the end of the experiment you will be given a final trial with an alternative display interface. For each trial you will be asked to follow a red guiding sphere through a virtual building environment. At various locations within the environment you will stop, point towards previously encountered locations, and estimate the straight line distance between your new location and the specified location. Between each trial you will have a short break, and after each main experiment trial you will be asked to draw a map of the path you traveled in the environment.

School of Interactive Arts + Technology (SIAT), Simon Fraser University Surrey
250 -13450 102 Avenue, Surrey, BC V3T 0A3 Canada
Tel: +1 778.782.7474 Fax: +1 778.782.7478 Web: http://www.surrey.sfu.ca

Following the final trial, the experimenter will conduct a short interview, and you will be asked to respond to a real world pointing task in the halls of SFU Surrey. The total estimated duration of this experiment is about one hour.

Potential risks for you, for third parties or society

Some people experience motion sickness while using virtual reality displays. If you have a history of motion sickness, please inform the experimenter. If you feel sick, or uncomfortable at any time during the experiment you should alert the experimenter and they will end the experiment. This will not affect your compensation in any way.

You will experience some conditions that involve movement of a tilting swivel chair. The equipment has been designed with the utmost care to be safe and reliable. However, if you feel unsafe or out of control at any time, please inform the experimenter and they will end the experiment. Again, your compensation will not be affected in any way.

Compensation

You will be compensated for your participation with your choice of either research participation credit or $10.

Acceptance of this Form

I understand that I may withdraw my participation at any time without penalties. I also understand that I may register any complaint with the Director of the Office of Research Ethics or the researcher named above or with the Chair, Director, or Dean of the Department, School or Faculty as shown below. I have been informed that the research will be confidential. I understand the risks and contributions of my participation in this study and agree to participate:

Participant First Name:____________________ Participant Last Name:________________________

Participant Contact Information (incl. email/phone): ____________________________________

Participant Signature: ____________________________________ Date: ______________

Appendix C.2

Experimental Evaluation: Participant Questionnaire

Questions During the Experiment

1) Pre-Test Motion Sickness Rating JOYSTICK (0-100%)
2) Post-Test Motion Sickness Rating JOYSTICK (0-100%)

3) Pre-Test Motion Sickness Rating SWOPPER (0-100%)
4) Post-Test Motion Sickness Rating SWOPPER (0-100%)

5) Pre-Test Motion Sickness Rating ALTERNATE DISPLAY (0-100%)
6) Post-Test Motion Sickness Rating ALTERNATE DISPLAY (0-100%)

Post-Virtual Experiment Questions

1) Age:
2) Gender:
3) Occupation:

4) Do you play video/computer games? (esp. 3D-games)?
5) If yes, how many hours/day do you play on average?

6) Do you engage in coordinated physical activity? (ping pong, other sports, dance, anything that involves phsyical coordination):
7) If yes, how many hours/day do you engage with these on average?

   How immersed did you feel for each of the interfaces (0 = not at all to 100% = fully immersed) Describe how each made you feel more or less immersed?
8) Immersion for SWOPPER [0-100%]
9) Immersion for JOYSTICK [0-100%]
10) Immersion for OCULUS RIFT [0-100%]
11) Immersion for PROJECTION SCREEN [0-100%]

12) Did you feel nauseous at all during the experiment? On a scale from 0 (as before the experiment, e.g., not nauseous) to 100% (really really nauseous). If nauseous, please describe and the how each of the interfaces involved influenced your experience of nausea?

13) How intuitive was the SWOPPER control? (0-100%)
14) How intuitive was the JOYSTICK control? (0-100%)

15) How well could you navigate and follow the red sphere with the SWOPPER? [0- 100%]

16) How well could you navigate and follow the red sphere with the JOYSTICK? [0- 100%]

17) Which locomotion interface was more difficult? Why?
18) Which locomotion interface was easier? Why?

19) For the Swopper chair, which display was easier to use it with?

20) Overall, would you prefer to use the chair or joystick for navigating this virtual world (a virtual architectural design)? Why? Please elaborate.

21) What did you think of the physical motion used from the chair? What was best/worst about it? How could it be improved?

22) How did you solve the task? Did you use any strategies?

Post-Real World Experiment Questions

23) How would you rate your everyday spatial orientation and sense of direction on a scale of 0 to 100? (0 - not very good at orientation/naviga tion, 100 - very good)

24) On a scale of 0 to 100, how intuitive was the pointing box for the real world orientation task?

25) How did you solve the task? Did you use any strategies?

26) How familiar are you with the area of SFU SIAT we moved through? [0- 100%]

27) How do you think you did on the task? [0- 100%]

Final Experiment Questions

28) Did anything bother you during the experiment?

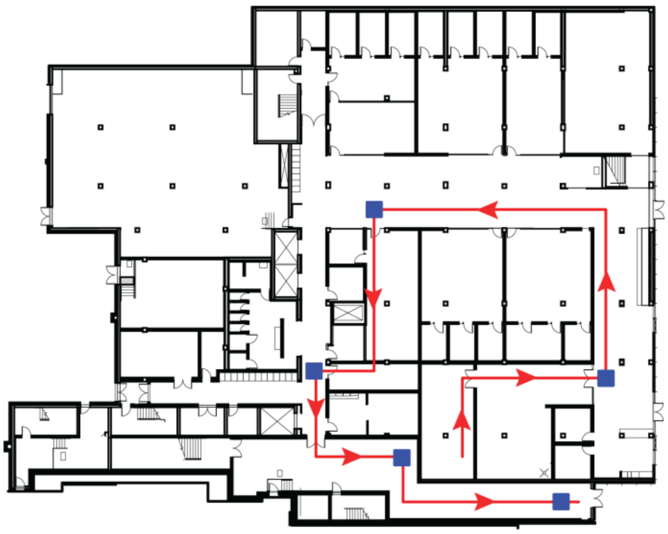
29) Any suggestions on what to change?

30) Any other comments?

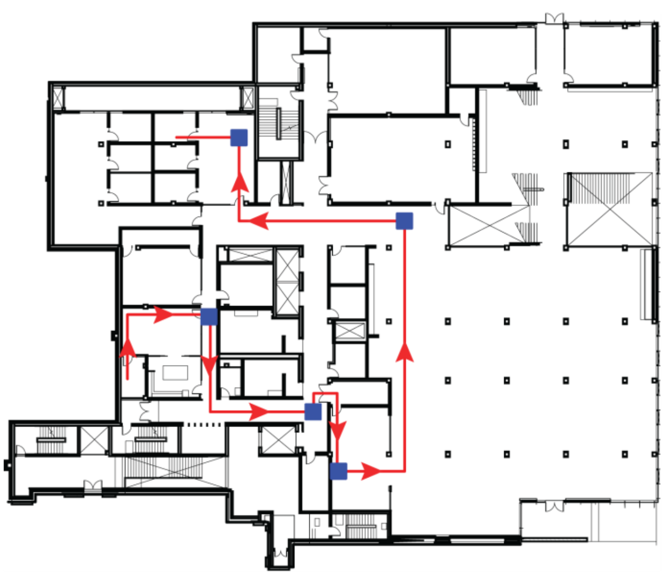
Appendix C.3

Experimental Evaluation: Map Drawing Task Responses

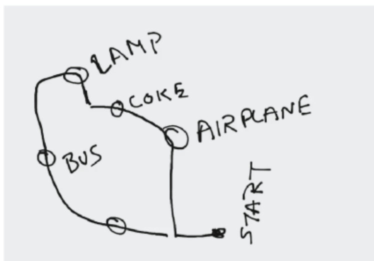
Environment 1

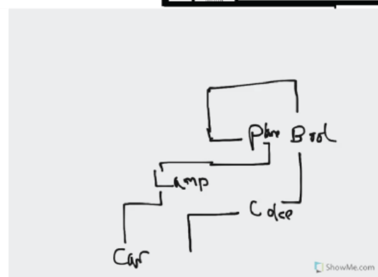


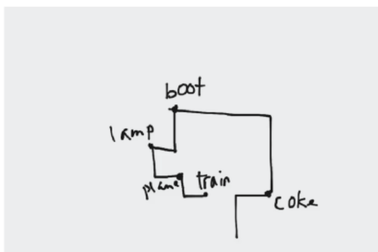
Environment 2

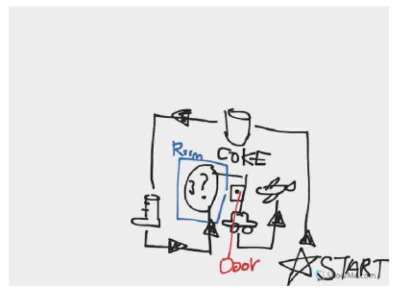


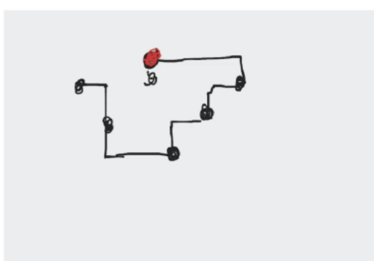
Environment 1 : 3D Projection Screen + Joystick

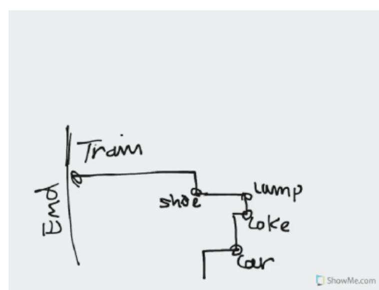


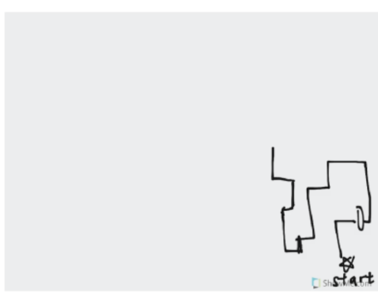


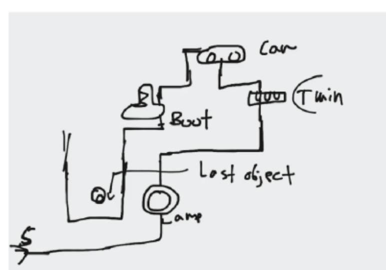




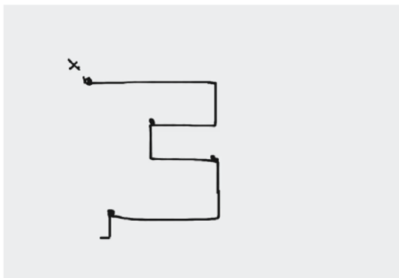


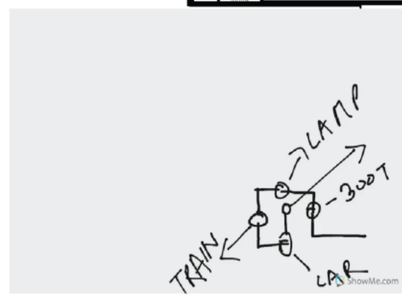


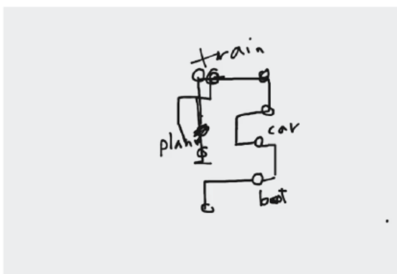


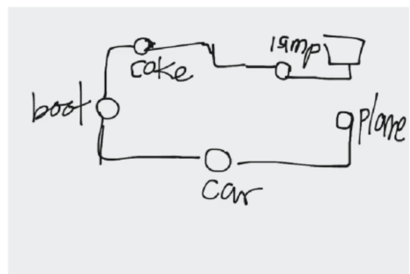


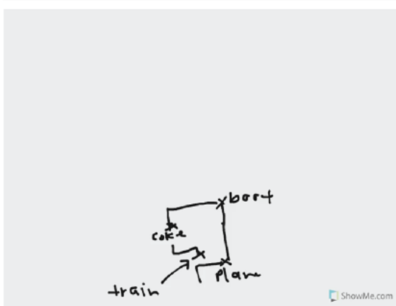
Environment 1 :
3D Projection
Screen + Swopper

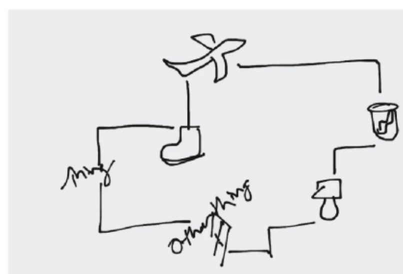


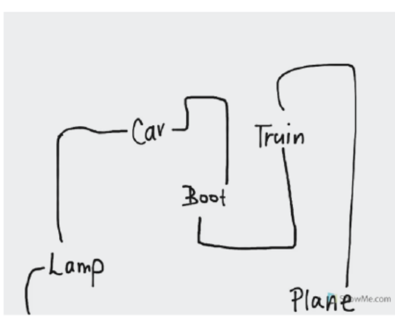


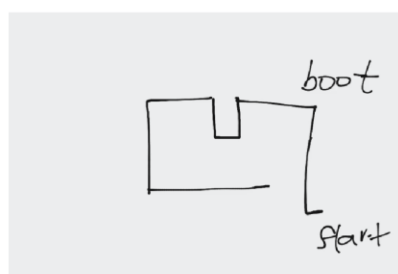




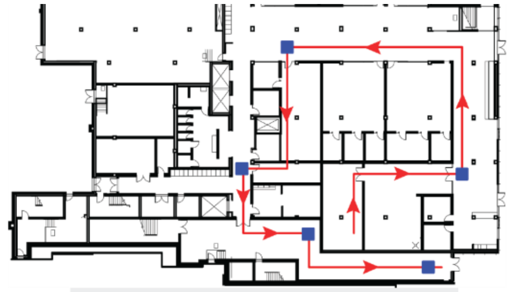


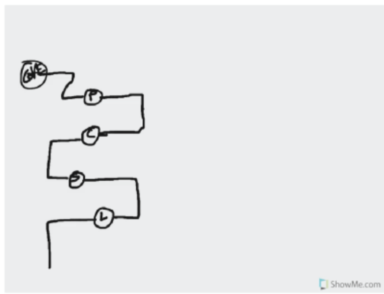


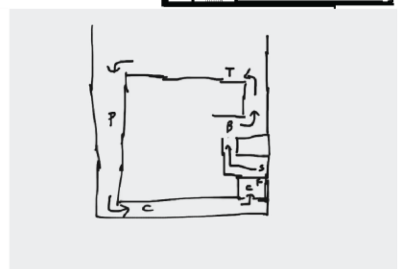


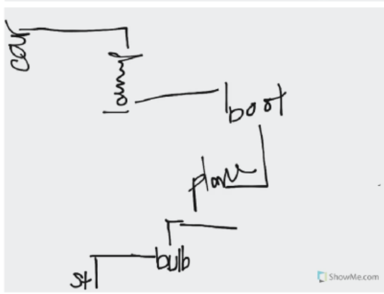


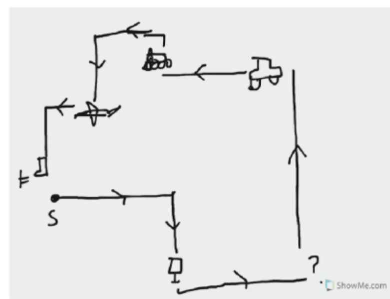
Envrionment 1 : Oculus Rift + Joystick

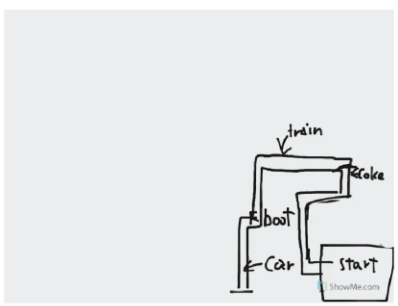


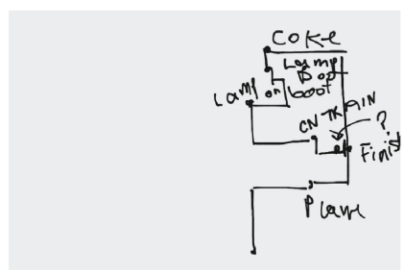


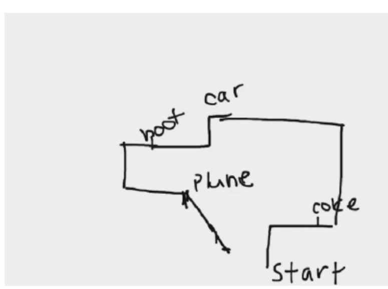


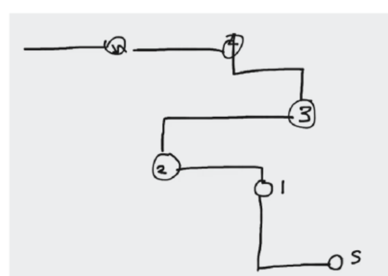




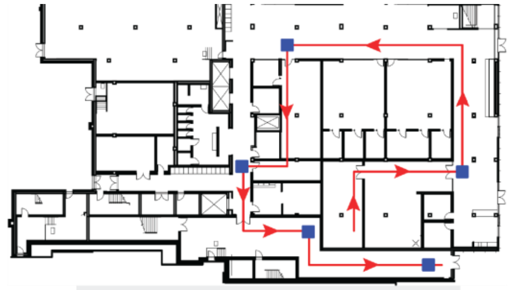


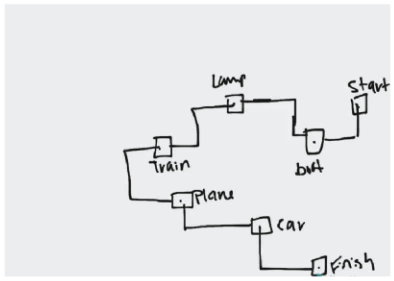


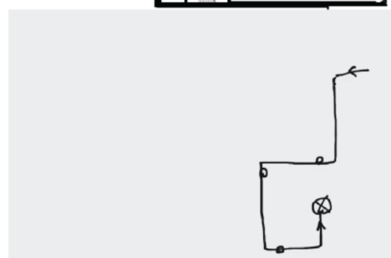


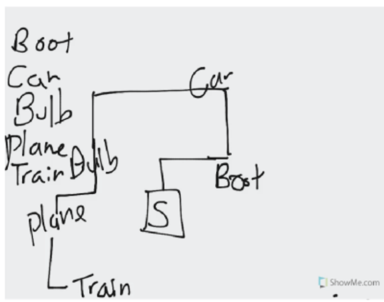


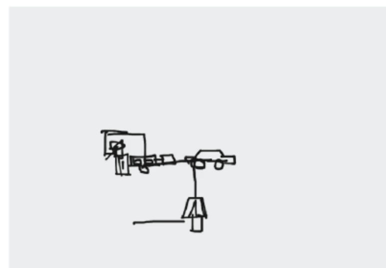
Environment 1 : Oculus Rift + Swopper

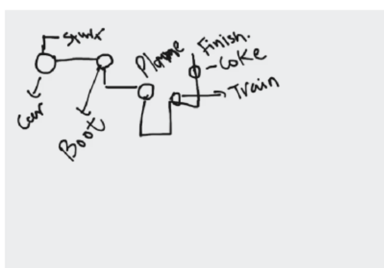


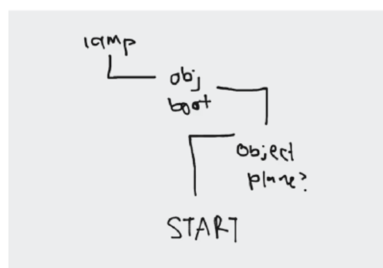


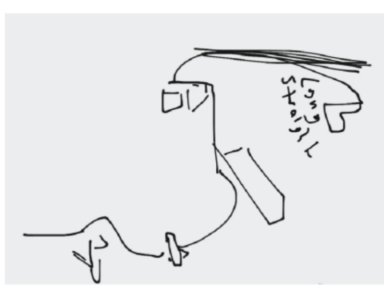


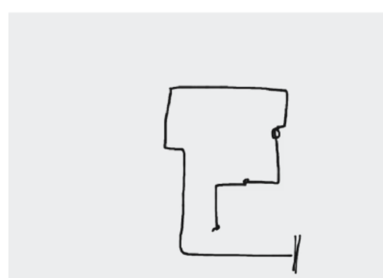




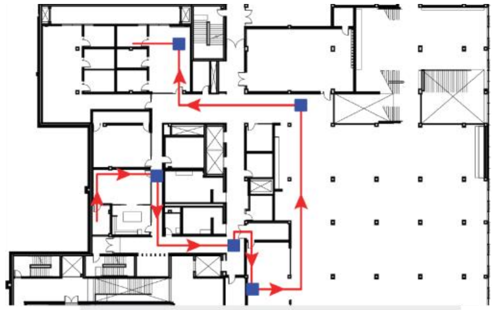


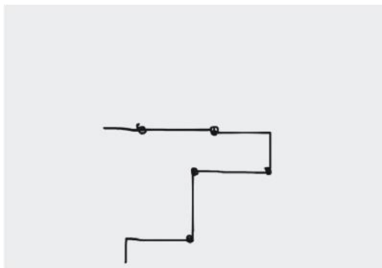


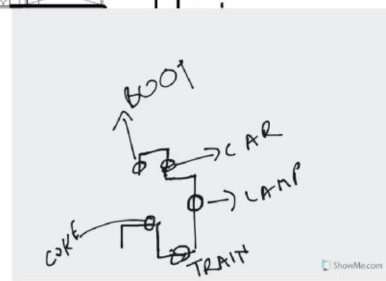


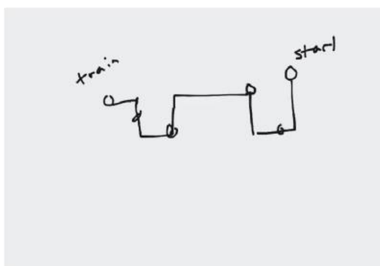


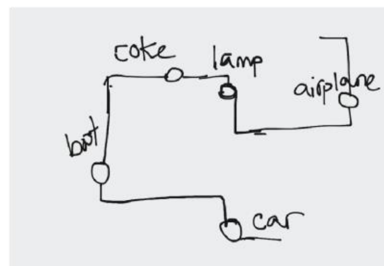
Environment 2 : 3D Projection Screen + Joystick

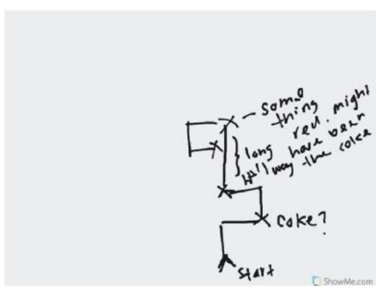


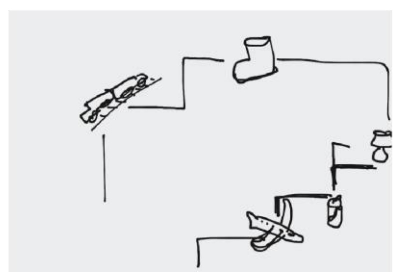


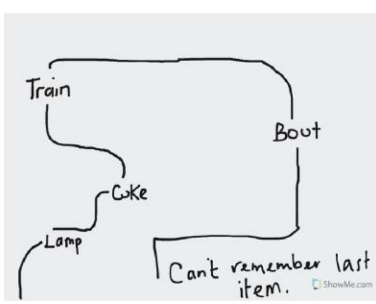


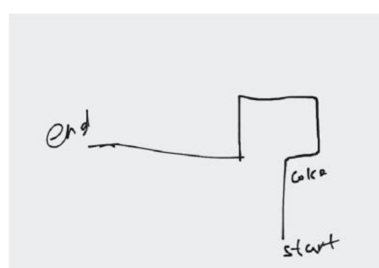




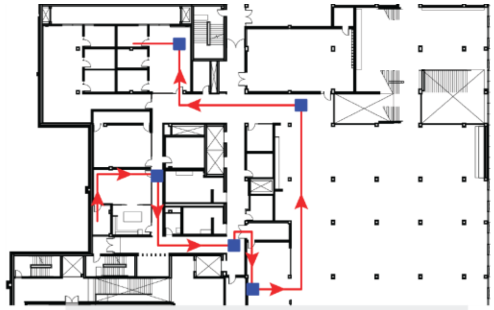


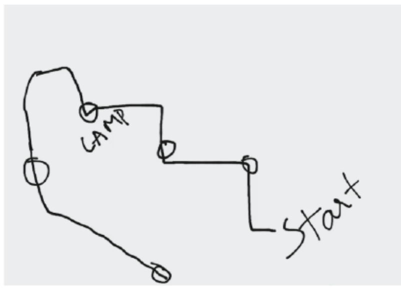


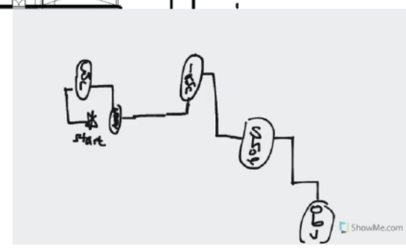


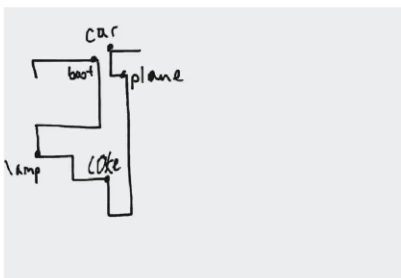


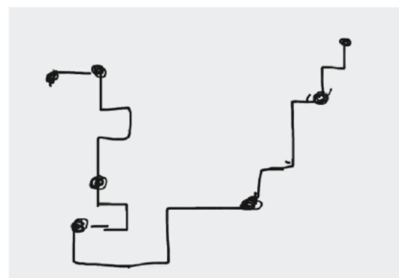
Environment 2 :
3D Projection
Screen + Swopper

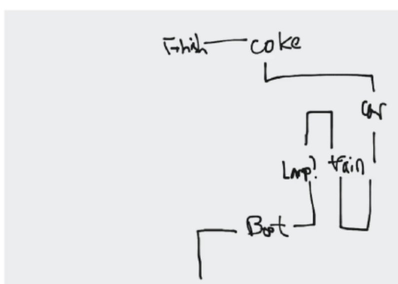


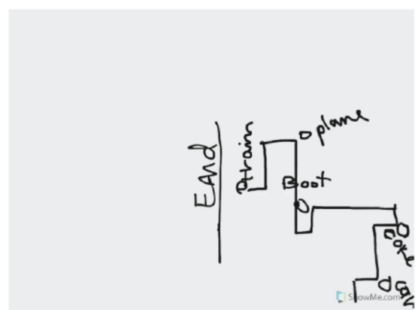


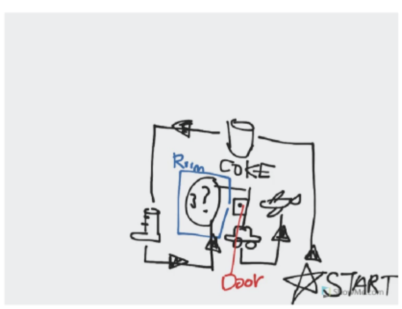


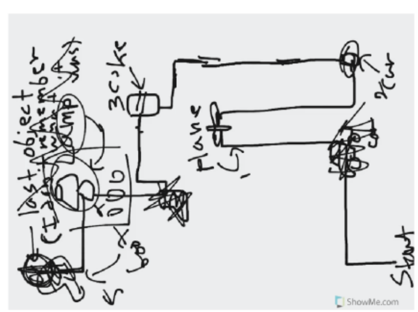




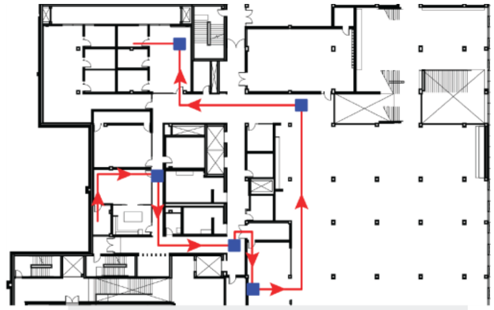


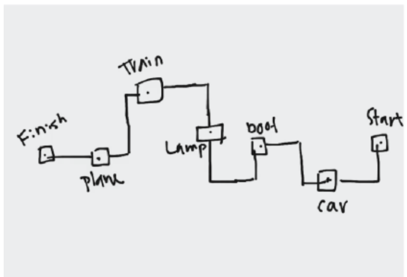


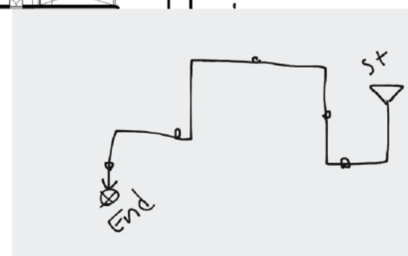


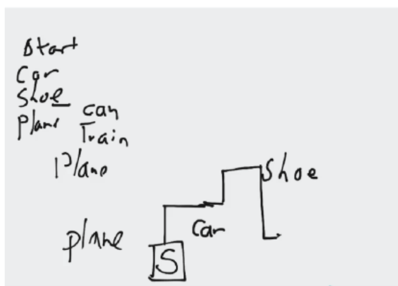


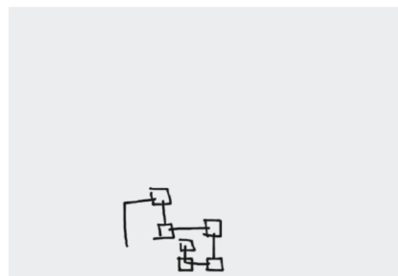
Environment 2 : Oculus Rift + Joystick

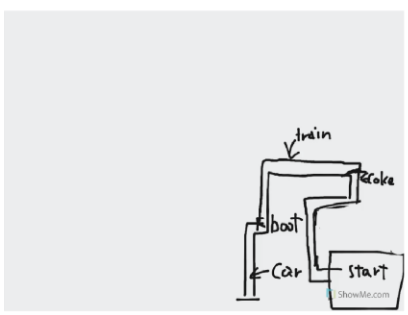


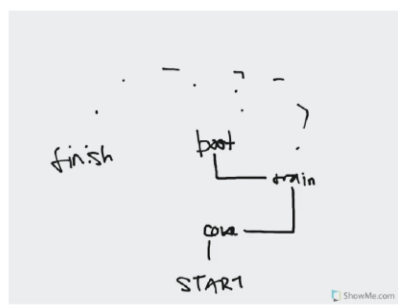


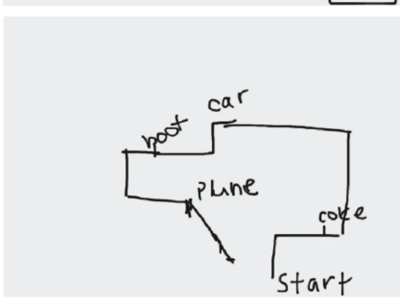


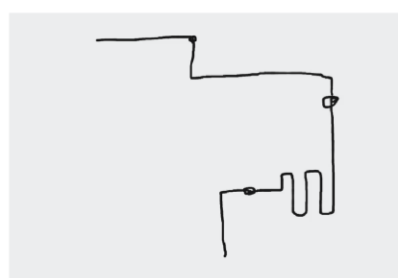












Environment 2 : Oculus Rift + Swopper