Computer Integrated Construction Research Program

EVALUATING RELATIVE IMPACT OF VIRTUAL REALITY COMPONENTS DETAIL AND REALISM ON SPATIAL COMPREHENSION AND PRESENCE

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ABSTRACT

In the last decade, Virtual Reality has become increasingly popular in the field of architecture. Virtual Reality represents computer generated three-dimensional environments that offer the viewer a convincing illusion and an intense feeling of being immersed in a mediated world. Architectural education has become a pertinent context for studying VR's potential as a learning tool. One of the challenges of architectural education is to help students acquire and improve their spatial visualization skills. For that purpose, different representational mediums have been used – from traditional drawings and physical models to more recent computer-generated environments that offer new ways of exploration. Given the importance that representational medium has in the process of visualization, studies have been performed in search of how new visualization tools could enhance this process.

This study is part of the larger research at the Immersive Environments Laboratory (IEL) at Penn State University that aims to examine which components of VR technology are most useful in helping novice students to better understand design. Based on previous research done in the IEL and current research, some of the variables have been identified to be of particular interest for further exploration. The goal is to examine the effects of VR display variables – ***screen size, field of view, and stereoscopic display;*** *and content variables –* ***level of detail and level of realism*** *on spatial comprehension and presence. Although VR has been identified as useful on architectural visualization as a whole, an understanding of how each variable relatively contributes is still lacking.*

To assess such complex technology, this study takes a variable-centered approach as its theoretical basis. The contribution of the five variables and their two-way interactions are estimated through a fractional factorial experiment with 84 subjects. Due to a magnitude of the project and large subject pool needed, this thesis being part of the joint proposal focuses on ***content variables*** *– level of detail and level of realism and elaborates separately on theoretical and background literature. For more in depth information on display variables refer to Nevena Zikic's thesis (n/d).*

The first part of the thesis gives an overview of the architectural design process and the role representational medium has during this process. The second part discusses current approach to VR in architecture and identifies VR components and important issues related to spatial cognition and presence. The level of detail and level of realism are further discussed in terms of depth cues and their role in perceiving and understanding space. The next parts deals with the theoretical framework for setting up the fractional factorial experiment and elaborates on the experiment design, procedure, measures used, scales, and results of statistical analysis. The last part discusses the findings and their meaning for future research.

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CHAPTER 1

Introduction

Architectural design process is an iterative visual process that uses representations. Designers use representations to externalize ideas conceived in their mind about the function and aesthetics of the virtual object. These representations help the designer to understand as well as communicate design ideas to others.

Students in the early architectural education are faced with the challenge of visualizing 3-dimensional structures and comprehending their often complex, spatial relations. To some extent, this is due to the fact that spatial concepts are mostly represented through plans and sections, which have a greater level of abstraction. Students have to use more mental effort to translate information from two-dimensional representation to imagine three-dimensional space. Given these, one of the main goals of architectural education is to develop and enhance students’ ability to visualize space. The ability to understand and visualize space is important for architects because it is central to the design process.

Process of visualization is greatly affected by the representational medium and the effort needed to interpret the information. This study builds upon the premise that the medium of representation can have a significant impact on the design process and thus, choosing an appropriate medium is of importance. Previous research suggests that traditional representational mediums such as drawings or scale models are limiting because of the additional effort needed in visualizing space and movement through it (Khlemani, Timerman, Benne, and Kalay, 1997). This is mainly due to the fact that the user has to extrapolate the scale of the model to one’s own scale.

On the other hand, virtual reality (VR) is becoming increasingly popular in the field of architecture due to its ability to present both small-scale and large-scale three-dimensional spatial information. VR in general implies a certain level of user-immersion in the computer-generated environment, though the extent of immersion may vary based on the context of application. The ITS/SALA Immersive Environments Laboratory (IEL) at the Penn State University is one of the first attempts to make VR accessible to students for design exploration. Recent work in the IEL has validated the usefulness of the VR system which offers students the opportunity to explore and evaluate their design in a more intuitive manner (Kalisperis, L., Otto, G. Muramoto, K. Gundrum, J., Masters, R., & Orland, B., 2002). Research so far have identified some of the VR display elements such as stereoscopy, screen size, and the field of view as contributing to an effective VR experience in architectural education.

The use of VR in architecture seems to be particularly helpful during the evaluation stage of architectural design process. At this stage, the role of representation is to communicate the design in a manner that allows for a meaningful criticism of the proposed solution. Architectural design process uses highly abstract representation in its early stages, especially when defining the design problem. As the design evolves, the representations become more detailed and more realistic to evaluate both function and aesthetics. Architects add more content elements such as furniture, textures, lights and shadows to enhance the appearance of the architectural space and thus further verify whether the space functions effectively. These elements affect one’s perception of space and understanding their contribution to spatial perception is also important.

Presence is a key component of the VR experience and its potential role on learning is an important area in VR research. This study aims to explore the effects of both display and content variables on spatial cognition and the sense of presence. VR is a complex technology and many studies have treated it as a monolithic technology. So far, an understanding of how some of the key attributes contribute to design comprehension is still lacking. This research will try to fill this gap by assessing relative contribution of variables such as stereoscopy, screen size, field of view, level of detail, and level of realism on spatial cognition and the sense of presence. This thesis being part of a larger research will focus more in depth on content variables – level of detail and level of realism. Display variables – stereoscopy, screen size, and field of view will be briefly addressed. For more detailed information and analysis on display variables refer to the paper presented at eCAADe Conference by Kalisperis et al. (2006), and unpublished thesis by Zikic (n/d).

1.1 Architectural design process

Architectural design process starts with problem recognition and problem definition in the early conceptualizing stages (Yessios, 1987). The final physical form evolves from numerous iterations of the proposed design solution. During the entire design process and throughout stages, architects use representations to externalize their ideas about the function and the aesthetics of the designed object. They use representations as a tool for understanding both the design problem and its solution. Design process is represented at different stages with varying levels of information. When defining the problem in the early stages of the design, designers use more symbolic and abstract representations such as diagrams, schemes, etc. During later stages, as design evolves, representations of the designed object become more detailed and illustrative of its intended physical appearance. External representations such as drawings, or scale models as well as internal representations in the form of mental images play an important role in the design process.

In architecture, great emphasis is put on the evaluation of the design. The design solution is evaluated to detect any possible failure with respect to program and function of spaces. It is necessary to understand the design in order to evaluate and critique it. Representations enable an understanding of the proposed design solution and allow for a meaningful critique (Kalisperis et al., 2002). A valuable external representation whether it is a drawing, a physical model, or a computer model, is therefore one that requires less deciphering or translation of the information and allows ideas to be communicated and thus evaluated more easily. By overcoming the cognitive limitations, an appropriate representation becomes a powerful aid in enhancing the reasoning and creative process (Rice, 2003; Balakrishnan, 2004).

1.2 Spatial Cognition

Cognition is broadly defined as a complex process that involves interaction of an individual's sensory-motor and neurological systems (Osberg, 1994). Spatial cognition represents an integral part of general cognition and can be defined in basic terms as one's understanding of space. Spatial cognition involves the processes of perception, storing, recalling, creating, and communicating spatial images (Osberg, 1994). Spatial cognition in the context of architecture has been variously defined as one's understanding of the proportions of a given space (Pinet, 1997), way finding or ones' ability to orient in a given space, or the relationship between various spaces (Henry, 1992).

Spatial skills when seen as a component of spatial cognition are generally defined as the ability to understand relationships between three-dimensional objects (Osborn & Agogino, 1992). In the context of architecture, spatial skills mainly involve the ability to mentally represent and transform three-dimensional objects, comprehend relationship between objects, and interpret images in the mind (Osberg, 1994). Spatial skills are important for architecture students since the discipline is concerned with the design of physical structures that are often very complex. For architecture students, the ability to visualize space is important for solving spatial tasks inherent in the design process. Mental rotation is a commonly used strategy for solving spatial problems in architecture design such as to determine if orthographic views match the isometric view and vice versa. Hence, one of the goals in the education of architects is to enhance spatial cognition and develop the ability to accurately perceive scale and spatial character through design representations.

1.2.1 The role of representational medium

Lack of spatial skills is mainly attributed to the inability in mentally rotating the 3D model, lack of depth perception or a limited sense of perspective (Trindade, 2002). These visualization skills are necessary components of spatial cognition in that they help individuals solve spatial problems by allowing them to form accurate internal representations. The ability to visualize space enhances spatial understanding by providing a crucial link between abstract representations and concrete experience (Trindade et al., 2002). The representational medium greatly affects the process of visualization. Rice (2003) argues that the medium of representation can have a significant impact on spatial cognition and creative process. According to Johnson (1997), poor external representations can affect internal representations by forcing the user to extrapolate and filter information, resulting in an inferior mental performance. For this reason, enhancing visualization skills and allowing for creative thinking greatly depends on the use of appropriate representation medium. For students in their early education this is also a challenging task.

1.3 Traditional medium vs. Virtual Reality

Khlemani, L., Timerman, A., Benne, B., and Kalay, E. Y., (1997) argue that traditional means of representation such as drawings or physical models contain only a small part of information about the building. The design is represented in drawings using graphic norms, conventions and symbols acquired through learning. These abstractions can communicate complex information about the design, its structural system, applied technology and materials. Being highly schematic or symbolic in nature, these representations require the designer to rely on his own intelligence and professional training to translate the information. Evaluation of traditional mediums also came to the conclusion that scale models, drawings etc, have difficulty to accurately represent three dimensional objects since they manage to introduce the third dimension only in a limited manner. This requires the user to exert more effort to visualize objects, spaces and the movement through them (Henry, 1992; Dorta, 1998). One reason for this is the effort to convert the scale of the model to correspond to own scale. Since the scale of the representational medium does not match that of the observer, the designer is more prone to misinterpret objects and spaces resulting in design errors (Dorta, 1998). Virtual reality or computer generated three-dimensional environment on the other hand, is becoming increasingly popular in the field of architecture as it offers the possibility to present both small-scale and large-scale spatial information without requiring the user to translate representation from 2-D to 3-D (Regian, J.W., Shebilske, W.L., & Monk, J.M. 1992).

Virtual reality provides the quality of experiential learning which is deemed as very useful in assisting the development of spatial skills. Regian et al (1992) argue that virtual reality is a superior learning environment for enhancing spatial skills because of its nature to maintain visual and spatial characteristics of the simulated world. Virtual reality provides an engaging environment which is stated to have a positive effect on students' motivation and learning (Dwyer, 1994). As a learning tool, VR allows students to create and experience their own creations as well as to manipulate the representations of others. It allows them to interact with worlds and phenomena that are not always accessible in the real world (Osberg, 1997). This is where VR could enhance the visualization process by augmenting the richness and recall of the information (Osberg, 1997).

When compared to VR, traditional medium is also limiting in that it is static in its nature and cannot represent movement through space and time. Visualization that includes time and motion conveys spatial information more easily, allowing the designer to make better judgments about space and form (Kalisperis et al., 2002). VR allows experiencing the effects of light, color, texture, reflectivity and contrast and the perceptual feeling they create. It allows the simulation of depth which is important for spatial cognition (Kalisperis et al., 2002). Virtual reality however, is not expected to completely replace but rather complement the information provided with traditional representational medium. Virtual reality is seen as very useful in communicating architectural ideas for critique when it is used alongside other modes of representation allowing the problem to be seen in different ways.

The main goal of VR systems is to enhance the three dimensional aspect of architectural space providing an instructional medium that can be very useful in aiding perception of the designed object. The field of architecture seems ideal for taking advantage of what VR has to offer, while considering various stages of the design process and its issues of representation, perception, cognition and design analysis. Since architectural design process works with visual and spatial data, it is an ideal context for studying the effects of VR technology on spatial cognition, as well as explore its potential in understanding the architectural design.

CHAPTER 2

Virtual Reality and Architecture

2.1 Virtual Reality Definition

There are numerous definitions of virtual reality (VR) depending on the context of its application. Virtual reality is commonly referred to as a computer-generated environment that offers the viewer a convincing illusion and an intense feeling of immersion in an artificial world that exists only in the computer. Virtual reality is thus often referred to as *immersion technology*. Virtual reality systems are mainly evaluated based on the extent to which the user can be immersed in and interact with it. Immersion and interaction are also stated to be factors that contribute to better learning and developing of higher spatial skills (Trindade, 2002). Trindade (2002) argues that immersion is helpful in situations where VR can represent concepts that don't have analogy in the real world experience. The ability to interact helps students learn better since they move from passive observers to active thinkers (Trindade, 2002).

In addition to these two factors, other researchers state that plausibility (Trindade, 2002) and fidelity, or information intensity (Heim, 1998) are also important characteristics of successful virtual environments to make believe that one is inside an artificial environment.

Virtual reality systems can be further classified into three categories, depending on the level of immersion that is induced:

- *Immersive* systems that involve the use of head-mounted displays or large screen displays that cover the viewer's field of view
- *Non-immersive* systems such as small screen displays that don't cover the whole field of view
- *Augmented* systems that overlay the virtual display over visual field as the user looks at the real world

2.2 Virtual reality in the context of architecture

Visualization using VR in the context of architecture deals essentially with space and volume conceptualization (Kalisperis et al., 2002). It enables an understanding of design as an "experience of the intended reality" (Brady, 1997). Students can explore their proposed design in a manner similar to how the space will be used. This visual expression can reinforce a holistic understanding of the physical reality of architecture.

Virtual reality is useful in architectural design during design pre-visualization to facilitate spatial understanding and evaluate for design revisions by providing immediate feedback (Otto, 1999). Evaluation of spaces is important in the design process since errors in perception can lead to erroneous judgments (Henry, 1992). Among other things, these designed spaces are more explicitly evaluated in terms of their sizes, relations to each other, and their individual qualities and attributes (Henry, 1992). The evaluation of the design becomes increasingly difficult as representations become more abstract (Kalisperis et al., 2002). Dorta (1998) argues that VR allows the designer to model and transform the space directly rather than in one's head. VR visualization techniques which can simulate depth convey spatial information more efficiently. This can reduce errors due to abstracted representation (Kalisperis et al., 2002). Rice (2003) reported that the implementation of VR in design curricula demonstrated that the students' ability to accurately visualize space was developing at a much faster rate.

The ITS/SALA Immersive Environments Laboratory (IEL) at Penn State University is one of the first to attempt to make VR accessible to undergraduate students for design exploration (Balakrishnan, 2004). The IEL now offers a three-screen, panoramic, stereoscopic virtual reality (VR) display. Recent work by Otto (2002) and Kalisperis et al. (2002) in the IEL have validated the usefulness of VR for architectural visualization by offering students the opportunity to explore and evaluate their architectural design projects at all stages. Encouraging students to design in three dimensions from the conceptual stage resulted in more alternatives to design problems[1]. Virtual reality allows students to understand better the design, both space and form, as well as texture and light as they explore spatial and temporal movement (Kalisperis at al., 2002). However, increasing the visual complexity of the design does need not result in a better solution. Architectural design goes beyond the visual aspect to include environmental, cultural, and social aspects and therefore, better visualization tools do not necessarily imply better designs. Nevertheless, given that the visual aspect is highly important to design, this study will focus on spatial understanding of the design and acquisition of spatial skills in design education of novices. This can lay the foundation for application of all other domains of architectural knowledge.

2.3 Virtual reality components and how they affect spatial cognition

As mentioned, VR in architecture deals in essence with conceptualizing and shaping forms and volumes. Space is determined in the most basic terms by its shape and size. Students mainly deal with tasks that require determining spatial properties such as location, size, distance, direction, shape, and movement. They not only learn to observe and understand space in terms of the form, proportion, scale, but also become attentive to light, color and texture and the perceptual feeling they evoke. The main reference for judging and evaluating spaces are scale and depth cues. According to cognitive psychologists depth perception is an important component of spatial cognition. By means of large displays that cover the user's field of view and the simulation of depth, VR technology has the capability to present spatial information in a more engaging manner, allowing for interaction with designed spaces at a human scale. The content of the displayed information can further augment the richness of information and possibly enhance the visualization process. Large screen size and wide field of view are identified as very useful VR components in that they allow for more spatial information and

[1] Design problems in architecture are defined as ill-structured problems that require flexible utilization of different domains of knowledge. It is argued that computers support the acquisition and flexible use of design knowledge which makes them appropriate in the early education. Since ill-structured nature of the architecture design problem is not the subject of this study, for more information refer to: Simon, H.A. (1973) "The Structure of Ill-structured Problems"

alleviate the scale problems characteristic of traditional media. Stereoscopy, texture, lights, shadows and objects contribute to the overall VR experience, but even more so, they act as depth cues affecting the perception of spaces.

2.3.1 Depth cues

There are two groups of depth cues. Primary (also referred as physiological) visual cues for the perception of depth are binocular vision (stereopsis) and motion parallax. Binocular vision further comprises of accommodation, convergence, and disparity. Accommodation is the ability to focus on one point at a time; convergence represents the angle subtended by the two eyes focused on an object; and disparity occurs when each eye receives a slightly different image.

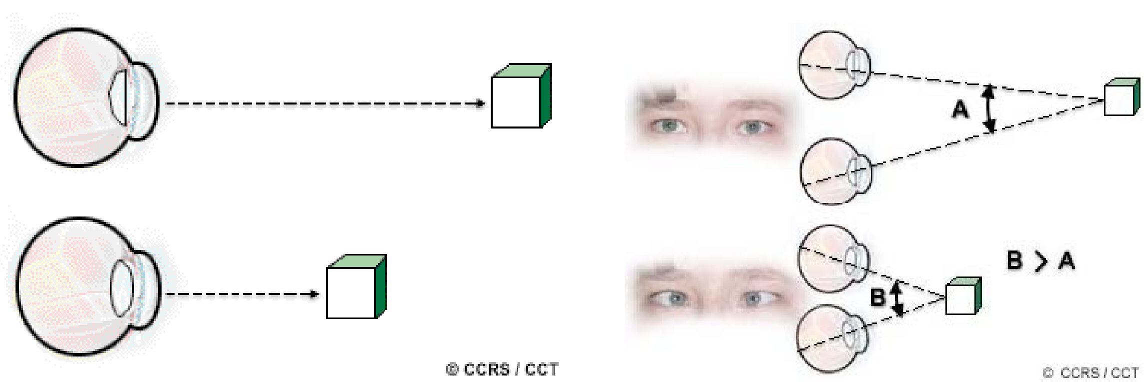

Figure 2.1 Accommodation (left) *and convergence* (right).
They are associated with the eye muscles, and interact with each other in depth perception.

Source: http://ccrs.nrcan.gc.ca/resource/tutor/stereo/chap2/chapter2_5_e.php

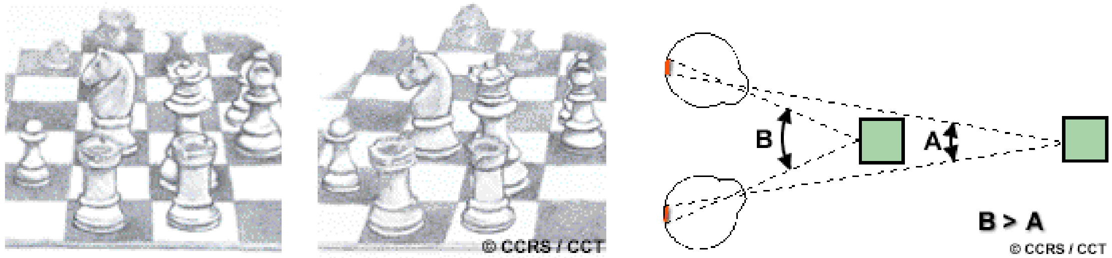

Figure 2.2 Binocular disparity.

The difference between the images of the same object projected onto each retina. If the convergence angle decreases depth perception becomes increasingly difficult.

Source: http://ccrs.nrcan.gc.ca/resource/tutor/stereo/chap2/chapter2_5_e.php

Figure 2.3 Motion parallax.

Objects closest to the observer will appear to move faster than those further away. This is an important cue to those who only have the use of one eye.

Source: http://ccrs.nrcan.gc.ca/resource/tutor/stereo/chap2/chapter2_5_e.php

In absence of these primary (physiological) cues, viewing monoscopic images relies on secondary (also referred as psychological) cues to depth: occlusion, linear perspective, size, texture, light and shadow, color, reference frame and haze (Porter, 1979; Michel, 1996). There is ongoing research about which depth cues should be used and how. Clarke, C.K., Teague, D.P & Smith, H.G. (1999) point to studies that show that while some cues complement each other to enhance depth, others counteract each other.

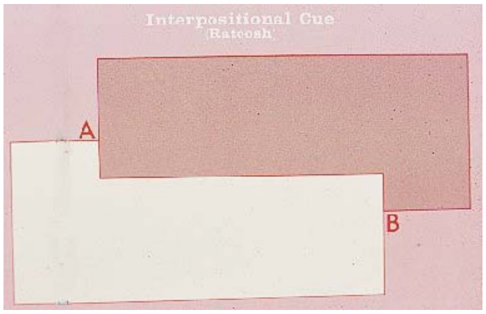

Figure 2.4 Occlusion.

Objects that are in front of other objects may partially block the view of the farther object. Assuming what the object should look like, we interpret the obstructed object as being farther away.

Source: http://www1.cs.columbia.edu/~paley/spring03/assignments/HW5/bg2020/

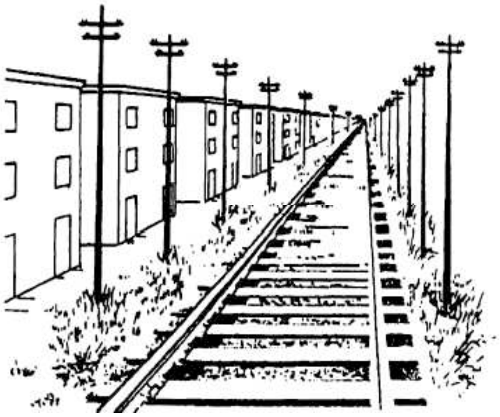

Figure 2.5 Linear perspective.

Object size reduces as the distance increases.

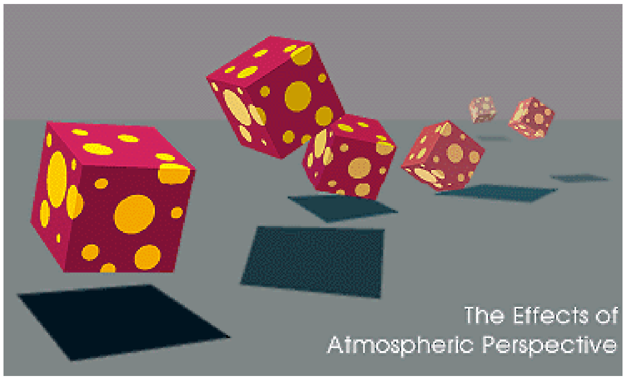

Figure 2.6 Aerial perspective.

Hazy objects are perceived as farther away.

Source: http://www.csus.edu/indiv/w/wickelgren/psyc110/Perception.html

2.3.2 Virtual reality display components: Stereoscopy, screen size, field of view

Stereoscopy is perhaps the most important characteristic of any virtual reality system. It enhances perception of three-dimensional objects on a computer screen through binocular disparity (Hubona et al., 1997) and therefore critical for spatial visualization.

Screen size has been also shown to effect spatial cognition. It has been argued that when viewing images on a small screen, the frame interrupts or obscures part of the foreground that extends to the eye of the observer (Rogers, 1995). This loss of information has some consequences on depth perception. Patrick, E., Cosgrove, D., Slavkovic, A., Rode, J.A., Verratti, T., and Chiselko, G. (2000) compared the effects of desktop monitor, large display and head-mounted display (HMD) on spatial cognition while navigating through a virtual environment. They found that users exposed to a large projection display performed slightly better in forming cognitive maps and attributed this to a higher level of presence. Henry (1992) and Plumert et al. (2004) have shown that limited field of view characteristic of HMD leads to underestimation of distances in virtual environments. Large screens, on the other hand, provide more spatial information thus making it easier to estimate egocentric[2] distances.

Field of view is another variable related to screen size that can potentially influence spatial cognition. Citing prior research, Arthur (2000) points out that narrow field of view in real world lowers human performance for navigation, spatial awareness, coordination and perception of size and space. Similarly in a virtual environment, a narrow field of view makes objects appear nearer (Arthur, 2000). Henry (1992) argues that narrow field of view resulted in consistent underestimation of distances in virtual environments.

[2] *Egocentric distance* is the absolute distance from one self. *Exocentric distance* is the relative distance between objects (e.g dimensions of the room). It is stated that egocentric distances tend to be more accurate than exocentric.

2.4 Virtual reality content elements: detail and realism

Architectural design progresses through different stages where representations take different forms depending on the level of information that needs to be communicated. Thus, the nature of design representation varies from more abstract forms in the conceptual stage to become more detailed and more realistic as design evolves. In addition to size and proportions, the perception of space is also influenced by light and shadow, textures and colors. Part of the education of architecture students is to become aware of how form, light, scale, proportion, color, texture affect one's perceptual feeling (Kalisperis, 1998). Virtual reality can be a useful tool at the stage of design where spaces need to be evaluated in terms of its function and "feel" (Henry, 1992). Here the design is evaluated both in terms of its aesthetics and program.

The role of these elements as depth cues and their effect on spatial perception has been of interest to researchers. Many a time, these terms are used interchangeably and refer to the same thing. In this study, for the purpose of better understanding the effects of the abovementioned cues, they will be grouped independently as *realism* and *detail.*

2.4.1 Realism

Realism is defined somewhat differently in different contexts. In the context of VR it generally refers to photorealism i.e. the degree to which representation visually resembles the depicted scene. The goal of many virtual reality systems is representational and functional isomorphism with its corresponding real world scenario. Representational isomorphism refers to how closely the virtual representation corresponds visually to the real world and functional isomorphism refers to how closely the virtual world behaves or reacts with respect to an analogous real world experience (Otto, 2002). While the functional isomorphism is usually achieved through navigational and behavioral constraints, the representational isomorphism is achieved through photorealistic rendering of the virtual world complete with textures, real world lighting, shade, shadows and color. In this context, we cannot talk about realistic and non-realistic (abstract) representations since we can never reduce realism to its absence. Even representations that involve greater level of abstraction can still remain realistic (Sachs-Hombach & Schirra, 2002). Photorealism is manly achieved through linear perspective, texture, light, shading and shadow. These are also important pictorial cues that are used in constructing and interpreting sizes, positions, and shapes of objects in the environment.

2.4.1.1 Texture

Texture and shadow are important cues in conveying spatial depth. Texture can provide information about distances depending on whether the texture is regular or stochastic, and whether it is forming a linear perspective gradient or a compression gradient (Gillam, 1995). The size of texture interacting with the shadow conveys information of spatial depth. Texture is a very efficient depth cue when it has a deep surface (Michel, 1996). It is more apparent when the object is closer and it appears more smooth and diffuse with increasing of distance. “Shadowed texture also gives visual ‘weight’ to form, a design aesthetic particularly applicable to architecture” (Michel, 1996).

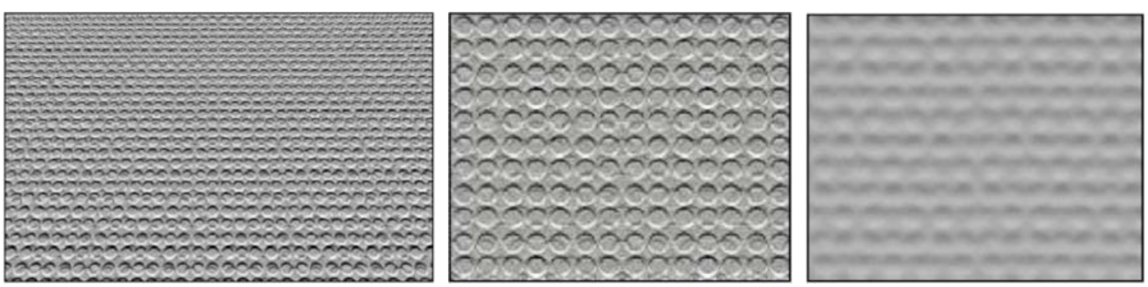

Figure 2.7 Texture as a depth cue.

Left: *texture gradient.* Middle and right: *sharper texture appears to be closer than the diffuse one*.

Source: http://www.ckk.chalmers.se/people/jmo/blender/textures.html

Although regular texture and a linear perspective appear to be more effective in perceiving depth and distances, more research is needed to determine the specific role of each of these factors on the perception of depth.

2.4.1.2 Light and Shadow

Surface shadow, or shading, gives the appearance of third dimension while the shadow cast by an object provides additional information about position of the object on the ground plane. Related to shadow is the direction of light that illuminates the object to provide information of spatial depth.

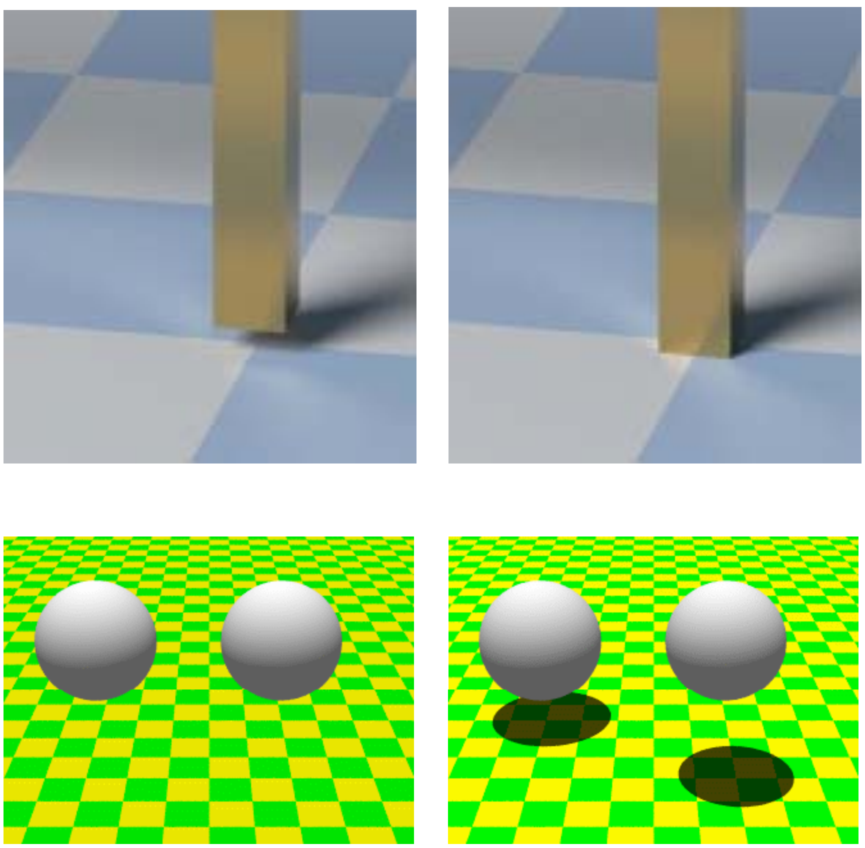

Figure 2.8 Shadow as a cue for the position of the object

Sources: above*: http://isg.cs.tcd.ie/campfire/billthompson.html,*
below*: http://www.ecs.cst.nihon-u.ac.jp/oyl/3d/Shinri/proof.html*

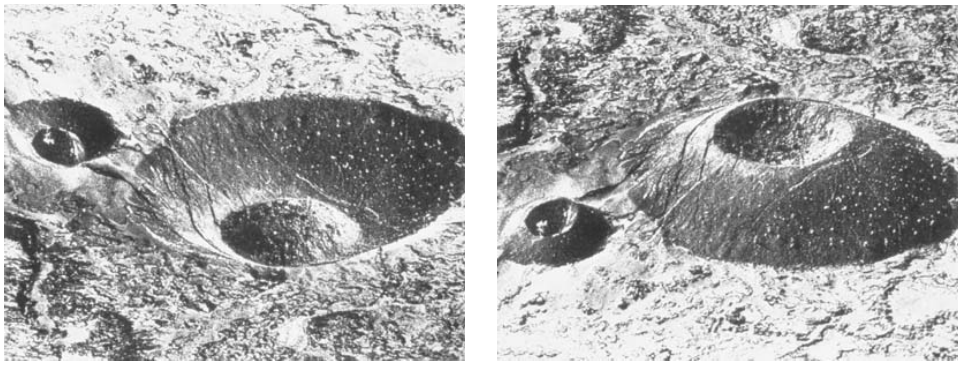

Figure 2.9 Shading as a cue

The crater becomes a mound after flipping the image, because of the assumption that light comes from above

Source: http://www-psych.stanford.edu/~lera/psych115s/notes/lecture8/figures1.html

There has been little support for the assumption that improved realism results in a more accurate assessment of spaces in terms of size. Comparison of photorealistic rendered and wire-frame representations by Hopkins (2004) did not show any differences in estimations of height, location of objects etc. Rice (2003) cites a study done by Holmes, Rice, Tomlison, and Hassenmyer (2001) comparing a model having lower level of realism consisting of simplified geometric forms, four colors, one light and no shadows; with another having more complex forms, unlimited colors, lights and shadows. The results failed to show any significant difference in the perception of scale and layout. On the other hand, in the same study the more realistic simulation was perceived as more similar in terms of light and shadows to the actual site.

There are different views regarding the level of information necessary for accurate evaluation of spaces. According to data-oriented approach, in order to sense the effect of the “real”, great quantity of data and detail is needed (Coyne, 1995). This is particularly reflected in the quest for a greater visual realism in computer graphics. On the other hand, according to constructivists our perceptions are primarily constructed from simple clues and cues from the environment. According to them, there is no need for a greater realism to be immersed in a virtual environment. The immersion depends entirely on our state of mind, experiences, expectations, interests, and our familiarity with the medium. We can be thus immersed in any environment depending on the context (Coyne, 1995).

Even though most VR systems strive for photorealism, some researchers argue that higher levels of abstraction are preferred in some situations to facilitate the decision-making by reducing visual clutter in the display. Others argue that the higher level of realism produces better learning (Zayas, 2001). It can be said that this mainly depends on the task at hand and its context.

2.4.2 Detail

The level of information increases towards the latter stage of design process. The design gets more refined and more detail is being added. Porter (1979) calls these elements that represent the necessary content of space sensory agents. When it comes to selecting components for architectural environment, size becomes a very significant depth cue. One of common mistakes that designers make is to over-size or under-size furniture, lighting fixtures or other furnishing, which gives a false perception of the space they are part of (Michel, 1996). Understanding how these cues affect the perception of architectural environment is therefore important.

There is ongoing research on the size-distance relation and one of the questions is whether the object of known size can influence the distance perception. Below are some examples of the inter-relation between perceptions of size and perception of distances. This is referred to as the size-constancy phenomenon. It refers to the fact that the size of an object is perceived to be relatively constant even though the size of objects can visually vary with distance. That is, if two objects of the same size are at different distances, the object far away will appear as smaller. The availability of objects of known size or yardsticks is crucial for scaling both real and pictorial space (Rogers, 1995).

Figure 2.10 The size-distance relation.

Left: Objects are perceived as having a constant size, therefore the smaller object is perceived as farther away. *Right*: size constancy collapses if distance information is removed. The woman on the right is perceived as much smaller than the woman on the left, since now they are assumed to be the same distance away.

Source: http://www-psych.stanford.edu/~lera/psych115s/notes/lecture8/figures3.html

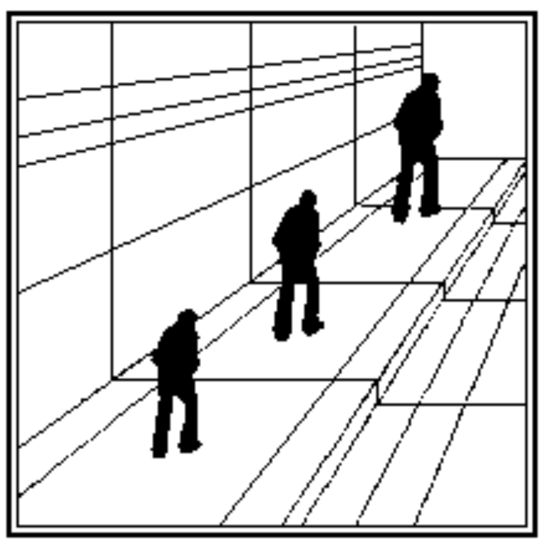

Figure 2.11 The size-distance relation.

Three figures are actually of equal size but perceived to be of different sizes because of the perspective introduced in the surrounding.

Source: http://www.aber.ac.uk/media/Modules/MC10220/visper02.html

One of the intrinsic factors affecting judgment of size and distance is the observer’s eye height. It has been argued that size judgments vary with distance cues and+ distance is more often inferred from the size judgments rather than measured. Although most research suggest that the ability to perceive distances and spatial layout increases with number of cues available, it is also stated that adding concordant cues for depth may result in an amplified perception of depth (Epstein, 1995).

Pinet (1997) studied the perception of space through comparison between modified virtual models; comparison of a foam core model with the virtual model, and comparison of the real space and its virtual representation. Participants were asked to estimate dimensions and crowding levels by observing objects added to the model. Comparison of slightly modified virtual models that were manipulated by adding furniture elements (windows, chairs and tables) demonstrated the tendency of participants to perceive space with added furniture and window as slightly larger. In estimating the crowding level of the same spaces, presence of window appeared to alleviate perceived crowding.

Henry (1992) demonstrated that sometimes, even objects of known size could be misinterpreted. His experiment evaluated how accuracy in perception of virtual spaces predicts perception of real spaces. He noted that an eight-foot door was perceived as six-foot high while a standard size chair next to the door was perceived as a child’s chair. A person added next to the chair was perceived as a child, until a child was added holding the person by the hand. This reveals an interesting aspect of people’s preference for certain cues over others. In this case, the doors were oversized, but participants instead perceived the chair as undersized and took the doors as the prevailing cue in scaling the space.

2.5 Research direction

Although Pinet (1997) demonstrated that scale figures, detail, and textures have great impact on the overall perception of space, there is little to confirm that improved realism in VR results in a more realistic assessment of spaces.

Given that perception is a very complex process, questions on perceiving and understanding space, depth, and layout have put more challenge on making a convincing portrayal of spatial relations in three dimensions. Nevertheless, Rogers (1995) reports studies which reveal that in general, perceived pictorial depth is underestimated relative to perceived real depth even when the geometric arrays from both the pictorial and the real scene are isomorphic. While this is confirmed in Henry's (1992) study where all distances are consistently underestimated compared to the real scene, Plumert et al. (2004) reports that depth perception in real environment corresponded to the one in the virtual environment. These differences in findings are probably due to different evaluation methods applied in these studies depending on whether the subjects were asked to estimate dimensions or to perform behavioral tasks such as throwing an object or walking.

Orientation is another aspect of spatial cognition that is increasingly studied in virtual environments. When it comes to way-finding and orienting in virtual worlds, Pinet (1997) argues that novice designers tend to get more confused and disoriented compared to experienced designers who often have a better intuitive sense of their position. Therefore, more research is needed to better understand way finding in VR and what cues are needed to improve orientation of the users.

Texture, lights, shadows, and size are very important cues to judge depth and hence of interest for many researchers, especially in the context of architectural design. These cues improve the designer's ability to manipulate and transform the shape and appearance of architectural space (Michel, 1996). These cues can be intentionally manipulated to achieve certain desired effects (e.g. shadows increase the sense of depth) which on the other hand can result in less accurate spatial perception (Houtkamp, 2004). Understanding how these cues influence the perception of spatial depth is therefore of importance. However, there seems to be confusion since level of detail and realism are interchangeably used in literature.

All the above mentioned VR components – stereoscopy, screen size, field of view, realism and detail for the purpose of this study have been identified as cues that play an important role in conveying spatial information and spatial depth. While their role in making quantitative and qualitative judgments about spaces is still under investigation, it is also speculated that they may play an important part in producing one essential feature of an effective VR experience – sense of presence. Sense of presence is stated by many authors (Witmer, 1998) as one of the critical aspects of any effective virtual reality experience.

2.6 Presence

2.6.1 What is *presence*

There are various definitions of the concept of presence depending on the field of research. Presence is generally defined as the subjective feeling of being present in a mediated environment.

Although the subjective sensation of "being there" is part of most definitions, presence is also referred as embodiment or the sensation that the virtual objects are perceived as real (Otto, 1999). Related to this idea is what Lombard & Ditton (1997) call object presence – the subjective sensation that an object exists in the user's environment. Object presence is closely linked to scene depth and greatly depends on depth cues such as stereopsis, motion parallax, accommodation and convergence (Stevens et al., 2002)

According to Slater et al. (1999, cited in Schuemie, 2001) remembering the virtual environment as places visited rather than a set of images is the key aspect of presence.

Witmer and Singer (1998) made the distinction between the spatial-constructive component – *immersion*, and the attention component – *involvement* and state that both are necessary for experiencing presence. While high levels of involvement can be achieved with media other than VR (books, movies etc.), immersion is entirely based on perceiving oneself as a part of the simulated environment. However, immersion remains a complex phenomenon and as Heim (1998) points out, what can be engaging for one person, need not be for the other.

2.6.2 Presence and learning

The role of presence in learning has been of interest for many researchers. According to Witmer (1998), interaction with the environment in a natural manner should increase immersion and thereby presence which will result in a more engaging and deeper learning. Osberg (1997) claims that the ability to create and manipulate worlds and phenomena that may have no parallel in the real world can stimulate students' imagination and visual thinking process. Interaction and immersion contribute to better learning and developing of higher spatial skills by moving students from passive observers to active thinkers and helping in situations when they have no analogy in reality (Trindade, 2002). The engaging environment which VR provides can have a positive effect on students' motivation and learning (Dwyer, 1994). In the field of architecture, possibilities of navigation through space would enable students to test ideas more thoroughly and foresee construction and potential conflicts, thus becoming more informed builders (Norman, 2001). The value of VR as an instructional medium lies in the opportunity for whole body experiential learning where students have the ability to create and experience their own representations in an interactive and compelling manner (Osberg, 1997).

2.6.3 Factors contributing to sense of presence

Presence is generally determined by characteristics of a medium and its user (Lombard & Ditton, 1997). Thus a large number of factors might contribute to creating the sense of presence. The characteristics of a medium determine the way information is displayed; the richness of the displayed information and the extent to which the user has the control over the VE (Witmer and Singer, 1998; IJsselsteijn, 2000).

Image quality, image size and viewing distance are characteristics of visual displays that are cited as important determinants of presence (Lombard & Ditton, 1997; IJsselsteijn, 2000). Image quality depends on characteristics such as resolution, color accuracy, sharpness, brightness, and contrast. If the image is displayed on a large display, it is expected that the users who are physically closer to an image would feel a greater sense of presence (Lombard & Ditton, 1997). Alongside high-resolution displays, wide field of view would be needed for better simulation of depth. Occlusion of objects by the display's edges would reduce the object-presence (Stevens et al., 2002). It is also argued that even though this would reduce the distraction from the VR experience, it is also possible that it wouldn't eliminate it.

The sense of presence depends on the level of visual correspondence between the virtual world and its analogous real world (representational isomorphism) and on the degree to which behaviors in the virtual world have a one-to-one correspondence with analogous real world experiences (functional isomorphism) (Otto, 2002). Related to representational isomorphism is the fidelity or plausibility of sensory information which also includes Steuer's (1992) notion of vividness. Witmer and Singer's (1998) realism factors suggest that pictorial realism governed by scene content, texture, resolution, light, etc., increases the sense of presence. Images which are more photorealistic, for example are likely to provoke a greater sense of presence. However, in communicating abstract ideas and concepts in architecture, the emphasis is usually on experiential congruence which is the degree to which virtual representation behaves as users "expect things to behave" based on accumulated life experience (Otto, 2002). This suggests that presence can be achieved by abstract representation as well (Otto 2002).

Research so far indicates that greater the level of realism the greater the sense of presence. Welch, Blackmon, Liu, Mellers, & Stark, (1996) reported a significant effect for pictorial realism on the sense of presence. On the other hand, Dinh et al. (1999) found that increasing visual realism and vividness did not lead to an increase in presence. He argues that increasing the level of realism hinders system responsiveness which results in reduced sense of presence in the virtual environment. This however, shows that the limitations in the system performance can affect the sense of presence without affecting perception of visual realism.

Although vividness and interactivity according to Steuer (1992) can greatly contribute to the sense of presence there is also a limit where these could result in sensory overload for the participant (Osberg, 1994).

In addition to motion and stereoscopy, many researchers have also suggested that a major influence on presence is the ability to interact with a mediated environment (Steuer, 1992; Lombard & Ditton, 1997; Wittmer & Singer, 1998). Interactivity here refers to the user's ability to influence and modify the form and/or content of the mediated presentation or experience (Steuer, 1992).

Presence remains a complex and multidimensional concept in that it does not depend only on the characteristics of technology but also the user. User variables identified as influential on the sense of presence are the user's willingness to suspend disbelief and her/his knowledge of and prior experience with the medium (Lombard & Ditton, 1997). In that sense, the same medium might generate a sense of presence in the user on one occasion but not another one, or one user's experience does not have to be the same as of another (Heim, 1998).

CHAPTER 3

METHOD OF INQUIRY

3.1 The research question

Given that VR in architecture mainly deals with conceptualizing form and space, the explorative and engaging nature of virtual environments makes it a powerful visualization tool for supporting the design process. Some of the VR components have been identified to have a significant effect on the perception of space by acting as depth cues. Grouping these components into content-based variables – level of *realism* and level of *detail*, and the display variables – *stereoscopy, screen size* and *field of view*, the goal is to determine their relative impact on spatial cognition and the sense of presence. It will be informative to know how these variables possibly interact and affect spatial cognition and presence. This study attempts to determine if the effect of screen size, field of view and stereoscopy on spatial cognition vary differently for varying levels of what is defined here as detail and realism.

The assumption is that the two or more independent variables may operate together having an interactive effect on an outcome measure. Various studies have looked at various combinations of depth cues such as relative size, stereoscopy, texture, shading, occlusion, motion parallax, and their combined effect on the perception of space and spatial layout. Gillam (1995) reports the findings on a strong interaction between stereoscopy and shading for example. It has been also stated that adding concordant cues for depth may result in an amplified perception of depth (Epstein, 1995). Nevertheless, further research on the effects of these variables defined as such, and their contribution to spatial cognition is still needed.

Presence as discussed previously is stated to be an important aspect of the VR experience. Because of the speculated role of presence in the learning process, in addition to assessing effects of the abovementioned variables on presence it is also of interest to determine whether an increased sense of presence eventually affects spatial cognition.

Although the ultimate interest is how VR can aid design comprehension, given the complex nature of the design knowledge and design comprehension, this study will focus on the impact of the VR on spatial comprehension as an important foundation for the design comprehension.

3.2 Research method

3.2.1 Variable centered approach

Numerous studies so far have been approaching VR as a monolithic technology without sufficient understanding of how specific VR system attributes such as screen size or stereoscopy contribute towards design comprehension. Virtual reality is a complex technology comprising of a number of component variables. The monolithic approach does not provide information as to which component contextually makes the most relevant contribution. In that sense, a better alternative would be to take a variable-centered approach as proposed by Nass and Mason (1990). As opposed to a monolithic, or box-centered approach, the variable-centered approach breaks down the technology into its component variables and their corresponding values. By taking this approach, the findings can have implications for all technologies, which have that particular value for a specific variable, making them more generalizable. This study aims to identify the key display and content specific elements of virtual reality systems and their relative contribution to spatial cognition.

In order to best explain the impact exerted by stereoscopy, screen size, field of view, level of detail, and level of realism (i.e. independent variables) on spatial comprehension and presence (i.e. dependent variables), experiment comes as the most appropriate research design for this purpose. Experiment primarily allows for higher internal validity by controlling for confounding effects and assuring that results are pertinent to the specific variables alone. The functionality of an experiment is in that it assesses the relationship between one or more independent and dependent variables. It allows an understanding of a unique impact of each independent variable on a dependent measure as well as interaction effects, or the joint impacts of two or more independent variables. In this case, heaving five independent variables each having two-level treatments and two dependent measures, the way to assess the main and interaction effects is using complex experimental designs known as *factorial* designs.

3.2.2 Fractional factorial experiment

For this research, a full-factorial design would have provided information on main effects, as well as all interactions. In a full-factorial experiment, for each complete replication of the experiment, all possible combinations of the levels of factors are investigated. A full factorial experiment for this study with 5 factors, each with two levels (i.e. a 2^5 factorial design), will have 32 treatment conditions requiring a very large subject pool with an academic background in architecture. Thus full-factorial experiment becomes very unpractical to run due to the sample size and number of experimental units.

Variable	Screen Size	Field of view	Stereoscopy	Level of Realism	Level of Detail
Levels	monitor 19"/ screen 8'x6'	1 screen / 3 screens	mono/stereo	High/Low	High/Low

Table 3.1 Five variables (attributes) each are having two levels.

In this research, the main goal is to identify which variables have the strongest effect. For this purpose, a fractional-factorial design, also known as screening design, will be used. A fractional factorial design is more appropriate here for a couple of reasons. The fractional factorial design is more efficient in terms of cost-benefit ratio compared to a full factorial design. The same five factors will be tested in 16 runs instead of 32 runs. Hence, two-level fractional factorial designs are extremely useful. However, by using fractional factorial designs we lose certain information regarding higher order interactions since we do not run experiments at all possible level of combinations, but only at a fraction of them. Since half fractional factorial design requires half the data that a full factorial design needs, it leaves room for running the other half of the experiment in order to complete the full factorial.

3.2.3 Experiment design

Given that resources in terms of time and subjects are limited, the priority of this study is to identify any main effect and lower order interaction effects that can affect spatial cognition and presence. Running 2^5 full-factorial design with five two-level factors would have 32 runs. This way, we quickly run up a very large resource requirement for runs with only a modest number of factors. The solution to this problem is to use only a fraction of the runs specified by the full factorial design. In order to keep both the number of experimental units and the number of subjects within reasonable limits the experiment was set up as a 2^{5-1} design[1] requiring 16 experimental units. Since there are five factors, the highest order interaction (screen size * stereoscopy * field of view * level of detail * level of realism) was used to generate the design. The design was of resolution V. Resolution describes the degree to which estimated main effects are confounded with estimated 2-level interactions, 3-level interactions, etc. Greater the resolution, the better the design and lower order interactions are much easier to interpret, providing us with actionable information. With a design resolution of V none of the main effects is confounded with other main effects or two-factor interaction.

In order to improve the internal validity of the experiment, all possible variables that could confound the study were controlled. Variables such as distance from the screen were maintained at constant levels. Demographic factors such as age, gender, height, academic major, academic standing and previous experience with the experiment facility were measured for statistical control.

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[1] In general, we pick a fraction such as ½, etc. of the runs called for by the full factorial. For 2^5 full-factorial with 32 runs, ½ fractional factorial would have 16 runs, ¼ fractional factorial would have 8 runs.

3.3 Operationalization of independent variables

As stated previously, visualization during the design process changes from highly abstract representations in the initial stages of the design to highly realistic and detailed ones in the later stages. For this study content factors – level of *realism* and *detail* were defined distinctly in order to explore their relative impact on spatial cognition as well as presence and how they might interact with screen size, field of view and stereoscopy.

3.3.1 Level of Realism

Representational and functional isomorphism with analogous real world scenario is the goal of many virtual reality systems (Otto, 2002). While functional isomorphism is usually achieved through navigational and behavioral constraints, representational isomorphism is achieved through photorealistic rendering of the virtual world. The term *realism* in this study refers to photorealism. In this sense we can have photorealistic representation or a representation that can be at greater level of abstraction but still remain realistic. To create different levels of realism – textures, real world lighting, shade, shadows and color were manipulated, all of which are identified as cues important for perceiving spatial depth. Low and high levels of realism were finally decided through pre-testing. Subjects were shown images with four different levels of realism and asked to rank each one on an eight-point Likert scale. Thus, the variable was confirmed to be valid since participants perceived its manipulations the same way as the researcher.

In high level of realism, all properties of textures; lights, shadows, reflection, refraction and shading were used, whereas for the low level of realism, textures were replaced with plain colors and reflection, refraction and shadows were discarded.

3.3.2 Level of Detail

As design evolves, designers further shape the space by adding more functional elements or details such as furniture, which not only add to realism but act as depth cues.

In this study, level of detail represents a group of objects used in a depicted scene that behave as depth, height, or width cues in addition to pictorial cues. To manipulate the level of detail, these elements were classified into four categories based on their function.

First category comprised of basic furniture elements such as dining table or bed, which help understand and evaluate the function of the space. Standardized fixtures such as doorknobs, light switches etc that could help determine the size and scale of spaces by means of their fixed size and placement with respect to the human height constitute the next important category. Third category included furniture elements such as shelves, that further contributed to understanding of objects relations, but not crucial in determining the function or size of spaces. The last category comprised of purely decorative elements such as plants that are not standardized, but might contribute to overall perception of space and contribute to a greater sense of presence.

During pre-testing the participants ranked each image with random combinations of different levels of detail, and it was decided to keep all four categories in the high-detail condition and in low-detail condition fixtures and decorative elements were discarded.

3.4 Stimulus

A six-minute long walkthrough of a two-story residence was used as stimulus for the experiment. The two-storey residence had the living room, dining room, kitchen, study room, restroom and laundry on the first floor and a master bedroom, guest bedroom and a bathroom on the second floor. A residence was chosen as the stimulus since most students are familiar with this type of building. It is generally stated that people who do not have prior experience with virtual environments can be easily overwhelmed and require time to adapt to the new environment. For these reasons, a simple model with a predetermined walkthrough was constructed. The model was developed using a 3D modeling software Form.Z™ and the animation was generated in 3d Studio Max™.

Even though navigability is an important feature of virtual environments, for this study, a predetermined walkthrough was used to control for individual differences in navigational abilities and to ensure consistency in viewpoints presented to subjects.

Figure 3.1a High Detail High Realism

Figure 3.1b High Detail Low Realism

Figure 3.1c Low Detail High Realism

Figure 3.1d Low Detail Low Realism

Figure 3.1 Combination of varying levels of realism and detail for the living room used in the stimuli

Sixteen variations of the stimulus were created based on the experimental condition. The level of detail and level of realism were either high or low and the stimulus was presented in either stereo or non-stereo. Screen size was manipulated by presenting the stimulus on either 19" desktop monitors or on large 8' x 6' rear projection screens. For the wider field of view, a 3:1 display ratio was used (presented on 3 screens) as opposed to 4:3 (single screen) for the narrow condition. Stereoscopic Player™ by

Berezin Stereo Photography Products was used for playing both mono and stereo movies. However, due to software limitations, in order to ensure consistency with respect to the length and speed of the movies in all conditions, the resolution of movies for the wide field of view (three screens) condition was reduced by 25% of the resolution of that of one screen.

3.5 Participants

Eighty-four participants were drawn from second through fifth year studios of the undergraduate program in the department of Architecture at Penn State University. Students of architecture were selected in order to control for the variability among subjects. They represent a homogenous group since they are all familiar with the tasks required in this study. The average age of the subject was 21.5 years (S.D.=1.75) and there were equal number of male and female participants.

3.6 Procedure

Participants were greeted on arrival and informed about the procedure. Their participation was voluntary and those willing to participate were required to sign the consent form. They were ensured to have a normal or corrected to normal vision and randomly assigned to one of the sixteen conditions and prior to the experiment. Participants were informed of the number of sections in the questionnaire, briefed about the nature of questions and requested to notify the researcher after each section was completed. Before the start of the experiment demographic information about age, major standing, and height was also collected. For the stereo condition, each participant was further tested for stereo blindness by viewing a short clip in stereo and confirming that he/she perceived the image as stereo.

Depending on the experimental condition, stimulus (walkthrough of a two-storey residence) based on the appropriate combination of different levels of the independent variables was presented to the participant. At the end of the clip, participants were asked to fill out the first section of the questionnaire that had 13 questions measuring presence.

Participants then watched the same stimulus again in five segments corresponding to exterior, living room, dining room, kitchen, and study room. The stimulus was paused at pre-determined points of each segment and the subjects were asked to fill out the section of the questionnaire pertaining to the view. Each section contained spatial tasks such as dimensioning tasks.

After viewing the last segment of the walkthrough participants were asked to complete the section containing questions regarding spatial organization, i.e. the location of various rooms with respect to other rooms above or below it. The purpose of these questions was to determine whether they had developed an understanding of the vertical organization of spaces. The spatial organization section of the questionnaire also asked the participants to sketch the layout of rooms within the given outline and reconstruct the path of their movement in the first floor.

The last section of the questionnaire related to computer use and prior experience with the virtual reality facility. After completion, the subjects were debriefed, requested confidentiality regarding the experiment and thanked for their participation.

3.7 Measurement

3.7.1 Spatial cognition

For this study, spatial cognition was operationalized as one’s understanding of the dimensions and proportions of the spaces, their scale in relation to the human body, location and relationship of spaces with one another, and way finding.

After viewing each space mentioned in the stimulus, the subjects were asked to estimate its height, width (measured in the direction of the width of the screen), and depth (measured in the direction perpendicular to the screen). Because of the small size of the building type chosen for the stimulus (residence) and the confined nature of the interior spaces, all the estimates were made from the corners of the room so that participants would have more spatial information.

In addition there were other tasks such as to estimate heights of objects in the scene and distance between different objects. Given that estimating space in metric units appears as less intuitive, to determine subjects' perception of the spatial dimensions in relation to their own body, they were asked to do several estimation tasks related to the number of steps required to walk from one point to another, or guessing how many people a space can accommodate etc.

It is also known that the experience of a new environment results in formation of a mental map. These cognitive maps play an important role in spatial cognition. They serve as a tool for way finding and therefore can be used to measure people's understanding of a spatial layout (Henry, 1992). In order to assess the knowledge of spatial organization and ability to retrace ones' movement through the residence, the subjects were asked to sketch the layout of various rooms on the first floor given the exterior outline. They were also requested to sketch the path of their movement. These responses were separately coded for their accuracy:

- In positioning of the rooms relative to each other,
- Of their proportions and
- Of the movement path.

The number of correctly positioned spaces formed another index. For proportioning part, spaces were rated in terms of the tolerance levels. Depending on the level of tolerance that would fall in, each space that was rated would receive between 2 points (max per space) and 0 points. Two coders coded each of the above responses and inter-codes agreement was 86%.

3.7.2 Presence

Presence was measured using a 13-item, 8-point Likert type scale adapted from the Igroup Presence Questionnaire (IPQ) by Schubert, Friedmann and Regenbrecht (2001), the Witmer and Singer (1998) Presence Questionnaire (PQ) and the Reality Judgment and Presence Questionnaire by Banos, Botella, Garcia-Palacios, Villa, Perpina and Alcaniz (2000).

The questions such as “To what extent did you feel you *were* physically in the house?”; “How realistic did the house appear to you?” or “To what extent did you feel you could reach into the house and grasp an object?” were used to measure ones’ sense of immersion and the extent to which objects were perceived to be realistic. The extent of the required mental effort for immersion was measured using questions of type “To what extent was it easy for you to get used to the house?” or “To what extent did the experience require a mental effort from you?” The third group of questions such as “How much did your experience in the house seem consistent with your real world experience?” and “How compelling was your sense of moving around inside the house?” measured the congruence of the walkthrough experience with reality.

3.8 Control measures

Variables that could potentially influence and confound the experiment outcome were measured for statistical control. Demographic factors such as academic standing, height, previous experience with computer graphics and virtual reality technology and extent of use, were measured to improve the accuracy of the analysis. Distance from the screen and the height of the chair where the participants were seated were kept at constant levels.

CHAPTER 4

RESULTS

4.1 Data analysis

4.1.1 Manipulation check

To ensure that the operationalization of low and high levels of detail was effective, a manipulation check was included in the questionnaire. The subjects were asked to rate on an eight-point scale how photorealistic various spaces in the residence were and how well furnished the different spaces were. An independent sample t-test assuming unequal variances was significant, $t(81) = -5.53$, $p<.01$ confirmed that subjects in the high detail condition perceived the stimulus as more detailed (M= 5.43) compared to the low detail condition (M=4.09). Similar significant test, $t(80) = -6.19$; $p<.01$ confirmed that the participants in the high realism condition perceived the stimulus as more photorealistic (M=5.43) compared to the low realism condition (M=4.00).

4.1.2 Index Construction

4.1.2.1 Presence

Since presence is a multi-dimensional concept, a principal component analysis was used to analyze the dimensionality of the thirteen items used to measure the concept. The scree plot and the criteria of eigenvalues greater than or equal to one were used to determine the number of underlying factors. Based on the above criteria, three factors were identified accounting for 63.23% of the variance. On rotation using a Varimax procedure, seven items loaded clearly onto the three factors with their highest loading exceeding 0.6 and the other two loadings less than 0.4. The remaining six items cross loaded across factors and were discarded from the analysis. The rotated solution yielded three factors, *level of immersion*, *ease of immersion* and *experiential congruence* with real world. The last factor consisted of only one item clearly loading and was therefore dropped from further analysis. The two factors were labeled *level of immersion* and *ease of immersion* based on the items loading on that factor.

Items for *level of immersion* measured the extent to which the subject felt “they were in the house”; the extent to which they felt they could “grasp an object in the house”; and how “real” those objects felt. Items for *ease of immersion* measured the “ease of getting used to the house”, the “ease of getting a good feel of the spaces”, and the “extent of mental effort required for the experience”. Thus two indices – level of immersion and ease of immersion – were created by averaging the three respective items and used for further analysis. This is more meaningful for interpretation and practical implementation of the findings than using a presence index created by additively combining the original 13 items even though such a scale would have had good reliability with a Cronbach’s alpha of 0.82.

4.1.2.2 Overall depth width and height estimation scores

For all estimation tasks, overall depth, width and height scores were computed. Since the distances that were to be estimated varied considerably, it was important to standardize them before combining. That was done by dividing each response by the correct distance. Thus a value of 1.0 would indicate an accurate estimation of distance, value above 1.0 would indicate over-estimation and less than 1.0 would indicate under-estimation. All standardized responses for the depth questions were averaged to create an overall depth score for open-ended estimation tasks. Similar scores were created for overall width and overall height, which were used for final analysis.

The final analyses were thus performed with the following dependent variables – level of immersion, ease of immersion, overall depth score, overall width score, overall height score, spatial organization score, proportioning score and way finding score.

4.2 Results

Analyses of Variances (ANOVA) were conducted to answer the primary research question of how the virtual reality system variables affect presence and spatial cognition. Wherever it was likely that one of the control measures could make a difference, they were added as covariates and Analysis of Covariance (ANCOVA) was performed to improve the accuracy of the findings. Since the covariates are not the focus of the analysis, the results for covariates are not reported here. Again, if interaction effects among the independent variables were found to be significant, the main effects of those variables are not discussed. Reported results are with p-value less than 0.1 instead of the norm of 0.05 since the primary interest is to reveal the trends, given that this is a screening experiment.

4.2.1 Level of immersion

For *level of immersion*, controlling for the extent of computer use, the analysis of covariance found a significant interactive effect between the field of view and detail, $F(1,65) = 5.41$, $p<.05$, between screen size and stereoscopy, $F(1,65)=4.11$, $p=0.1$ and also between detail and stereoscopy $F(1,65)=6.05$, $p<.05$.

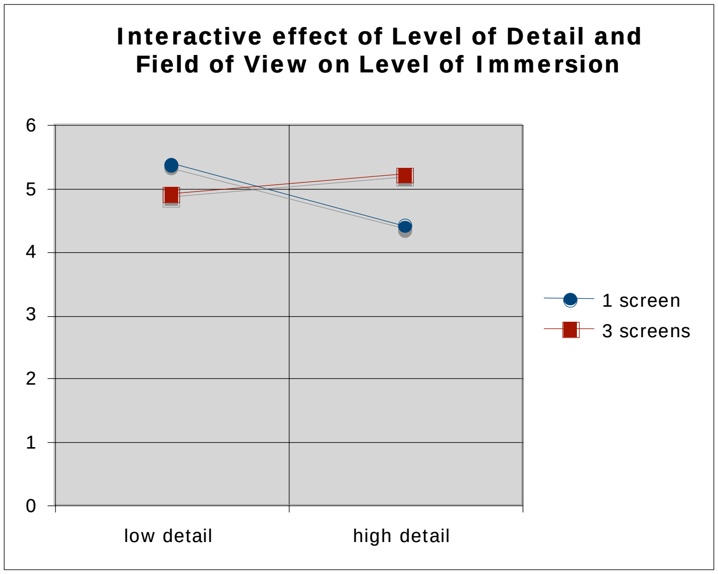

Figure 4.1 Interactive effect of level of detail and field of view on level of immersion

For low level of detail, narrow field of view has a greater level of immersion (M=5.37) compared to wider field of view (M=4.90) whereas for higher level of detail, the level of immersion is greater for wider field of view (M=5.21) with respect to narrow field of view (M=4.40) (*Figure 4.1*).

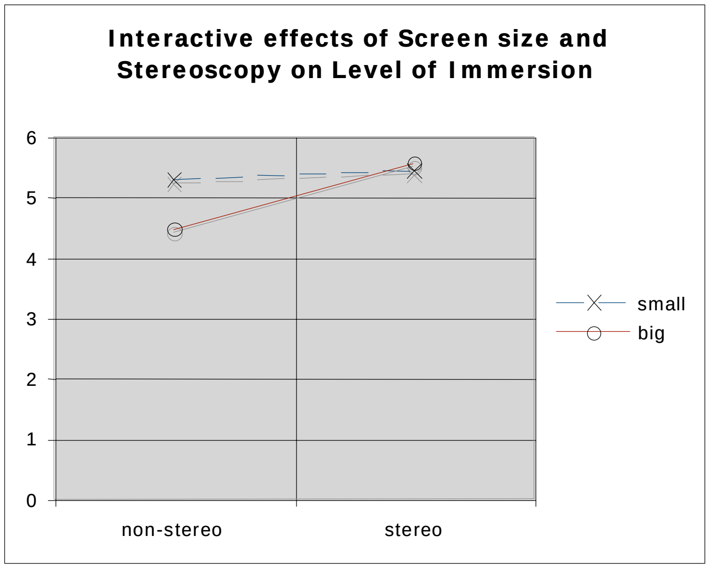

Figure 4.2 Interactive effect of screen size and stereoscopy on level of immersion

For smaller screen size, there is hardly any difference in level of immersion between stereo (M=5.44) and non-stereo (M=5.29). However, for larger screen size, the level of immersion is much greater for stereo condition (M=5.56) when compared to non-stereo condition (M=4.47) (*Figure 4.2)*.

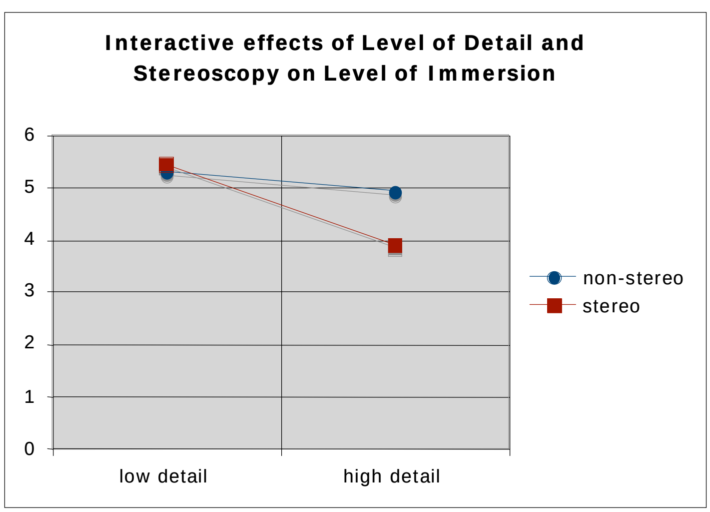

Figure 4.3 Interactive effect of level of detail and stereoscopy on level of immersion

For low level of detail, there is little difference in level of immersion between non-stereo (M=5.29) and stereo (M=5.44) condition whereas for the higher level of detail, the level of immersion is greater for non-stereo condition (M=4.91) compared to stereo condition (M=3.90) *(Figure 4.3).*

4.2.2 Ease of immersion

For *ease of immersion*, controlling for the extent of computer use, there was a significant interactive effect between screen size and field of view, $F(1,63)=3.27$, $p<0.1$ and also between field of view and realism, $F(1,63)=3.37$, $p<0.1$.

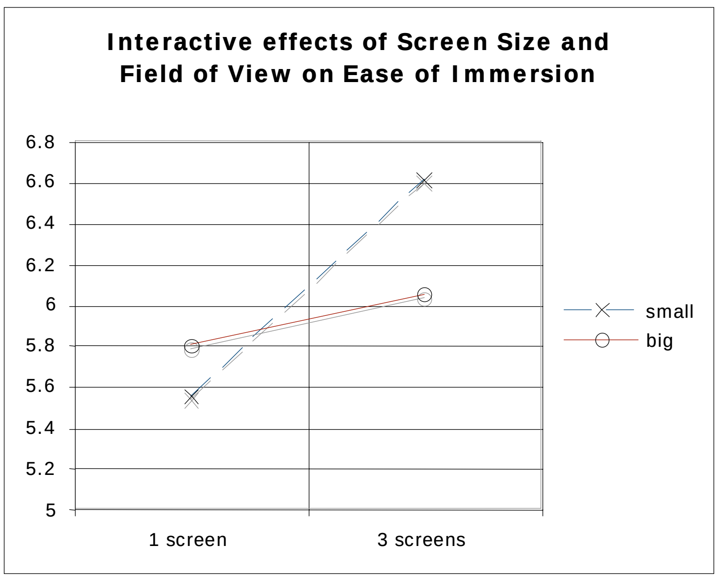

Figure 4.4 Interactive effect of screen size and field of view on ease of immersion

For larger screen size, there was hardly any difference in the ease of immersion between the narrow (M=5.80) and the wide field of view (M=6.05), however for smaller screen size, the ease of immersion was greater for the wide field of view (M=6.61) compared to the narrow field of view (M=5.55) (*Figure 4.4)*.

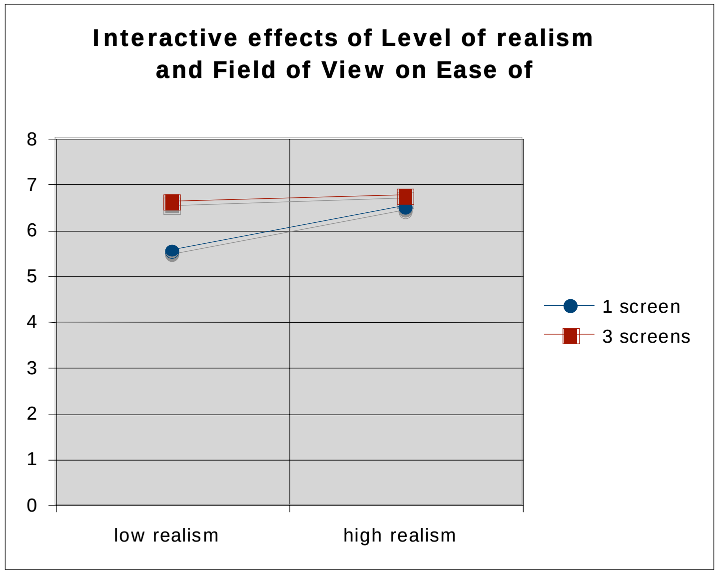

Figure 4.5 Interactive effect of level of realism and field of view on ease of immersion

For the wide field of view, the ease of immersion was almost the same for low (M=6.61) and high realism (M=6.74) conditions whereas for the narrow field of view, the ease of immersion was much greater for the high realism condition (M=6.50) compared to the low realism condition (M=5.55) *(Figure 4.5)*.

4.2.3 Depth estimation

Controlling for subjects' academic standing (year of study), analysis for *overall depth score* revealed significant interactions between screen size and level of detail, $F(1,64)=4.49$, $p<0.05$ and between field of view and level of realism, $F(1,64)=7.80$, $p<0.01$.

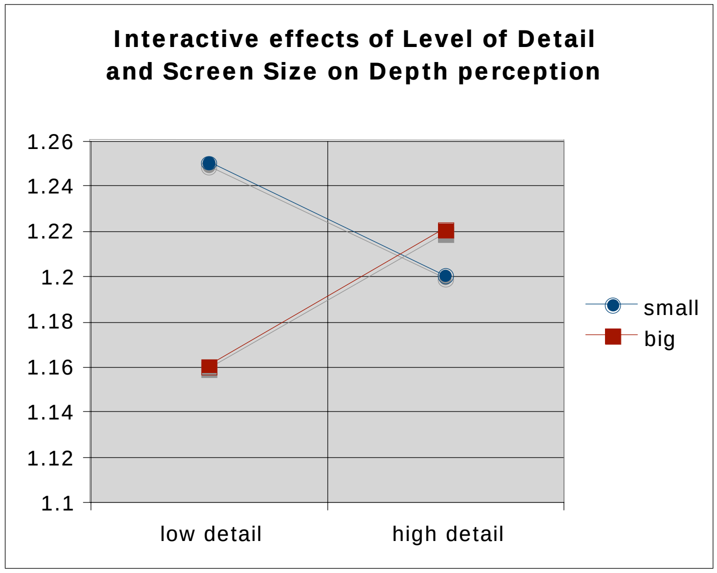

Figure 4.6 Interactive effect of level of detail and screen size on depth estimation

For the high level of detail, there is hardly any difference in depth perception between smaller (M=1.20) and larger screen size (M=1.22) whereas for the low level of detail, those in larger screen condition (M=1.16) tended to estimate the depth more accurately than those in the small screen condition (M=1.25) *(Figure 4.6)*.

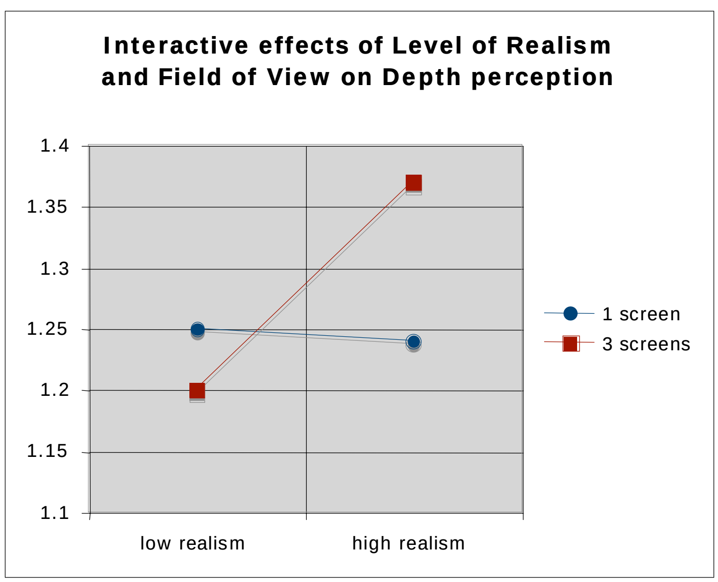

Figure 4.7 Interactive effect of level of realism and field of view on depth estimation

For the narrow field of view, there is hardly any difference in depth perception between those in the low level of realism (M=1.25) and high level of realism (M=1.24). However for the wide field of view, those in high level of realism (M=1.37) tend to greatly overestimate the depth compared to those in the low level of realism condition (M= 1.20) *(Figure 4.7).*

4.2.4 Width estimation

For *overall width score*, controlling for the subjects' academic standing, there was a significant interactive effect for field of view and realism, $F(1,63)=9.28$, $p< 0.05$.

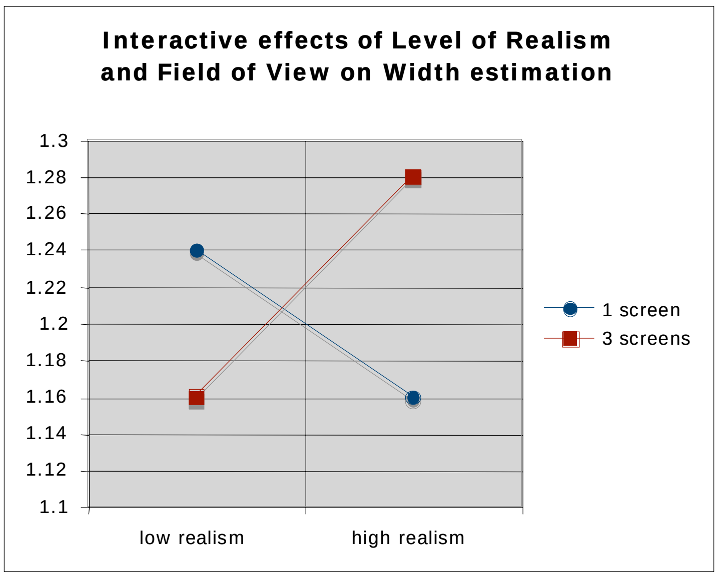

Figure 4.8 Interactive effect of level of realism and field of view on width estimation

For low level of realism, narrow field of view resulted in greater overestimation of overall width (M=1.24) compared to wide field of view (M=1.16). Where as, for high level of realism, the opposite holds true with wide field of view resulting in greater overestimation (M=1.28) compared to narrow field of view (M=1.16) *(Figure 4.8).*

4.2.5 Height estimation

For *overall height score*, controlling for the subjects' academic standing, there was a significant interaction between screen size and stereoscopy, F(1,60)=5.49, p<.05 as well as between level of detail and stereoscopy, F(1,60)=3.73, p<0.1.

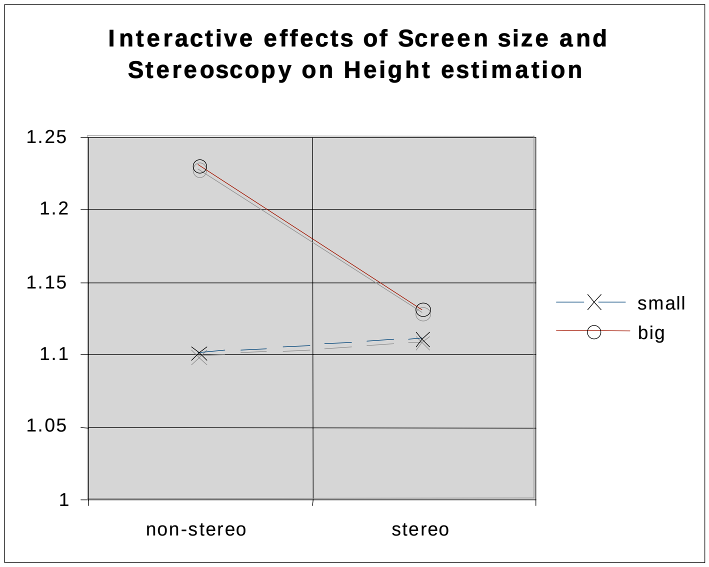

Figure 4.9 Interactive effect of screen size and stereoscopy on height estimation

For smaller screen size, the overall height estimation was more or less accurate for both stereo (M=1.11) and non-stereo condition (M=1.10) whereas for the larger screen size, those in non-stereo condition (M=1.23) tend to overestimate the overall height compared to stereo condition (M=1.13) *(Figure 4.9)*.

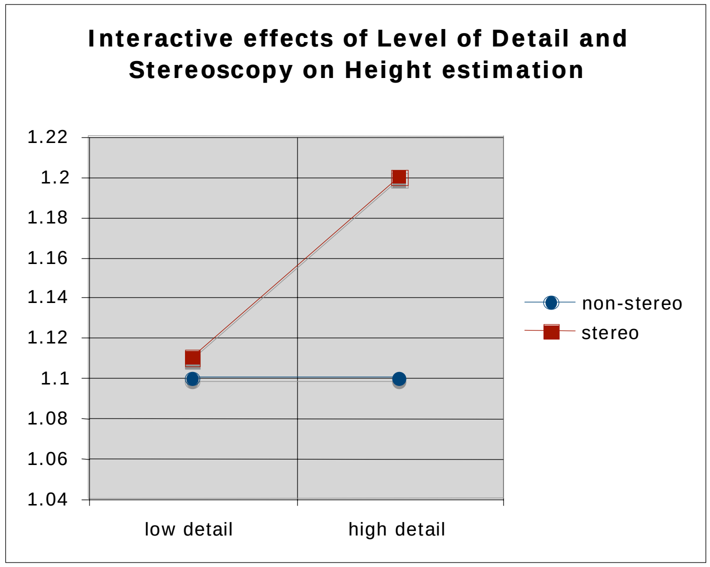

Figure 4.10 Interactive effect of level of detail and stereoscopy on height estimation

For non-stereo, there was no difference between low and high detail (M=1.10) in estimating overall height. However, for the stereo condition, high level of detail tends to result in overestimation of overall height (M=1.20) compared to low detail (M=1.11) *(Figure 4.10)*.

4.2.6 Spatial organization

In general, maps of the relative positioning of spaces were relatively accurate throughout conditions. Controlling for subjects' experience with computer graphics and academic standing, there were significant interactions between screen size and stereoscopy, $F(1,60)=4.04$, $p<0.05$ as well as between level of detail and stereoscopy, $F(1,60)=3.43$, $p<0.1$ for *spatial organization score*.

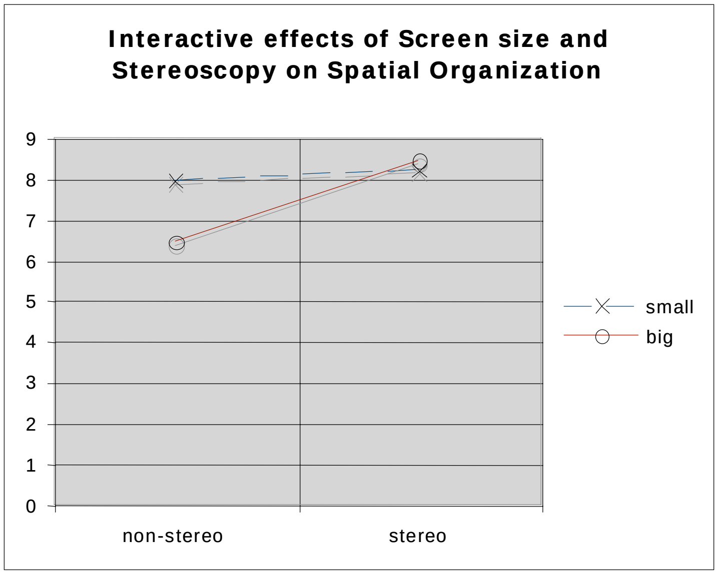

Figure 4.11 Interactive effect of screen size and stereoscopy on spatial organization

For smaller screen size, there was little difference in understanding spatial organization between stereo (M=8.22) and non-stereo condition (M=7.95) whereas for the larger screen the score was much lower for the non-stereo condition (M=6.46) compared to stereo condition (M=8.44) *(Figure 4.11)*.

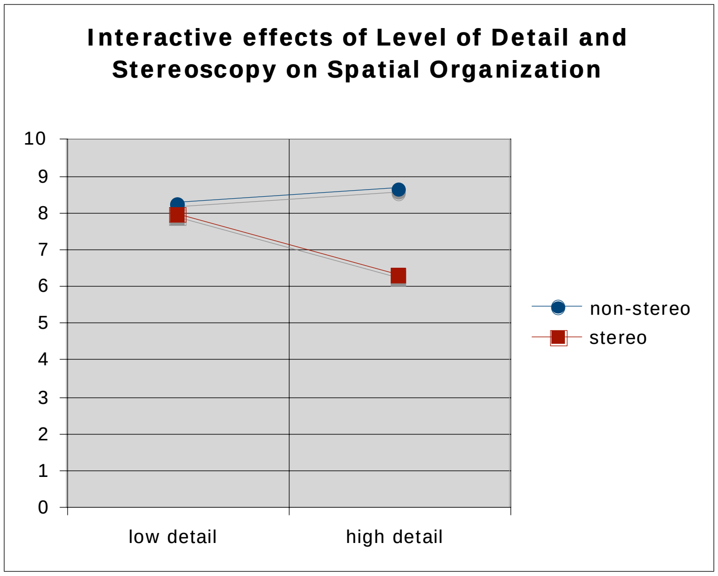

Figure 4.12 Interactive effect of level of detail and stereoscopy on spatial organization

For low level of detail, there was little difference in spatial organization score between stereo (M=7.95) and non-stereo condition (M=8.22). In the high detail condition, the score was much lower for the stereo condition (M=6.30) compared to non-stereo condition (M=8.62) *(Figure 4.12)*.

There were no however significant findings for the proportioning score or way finding score in the analysis suggesting that there was little difference between the experimental conditions in their influence on the two scores.

CHAPTER 5

DISCUSSION

The results indicate a general tendency for students to overestimate dimensions in VR across all conditions. Contrary to previous findings that distances are systematically underestimated in a VR environment (Henry, 1992; Epstein & Rogers, 1995; Messing & Durgin, 2004); depth, width, and height were all perceived to be larger than they actually were. This inconsistency with the previous research might be due to the greater field of view provided by large screens, as opposed to the head-mounted displays used in the above mentioned experiments, that are known to have a limited field of view. Another explanation might be that since the size of the building type (the residence) used in this study was relatively small and because most estimations were made indoor, all the distances were less than 40 feet, beyond which people are said to underestimate distances in a greater amount (Plumert et al., 2004).

Since this study focuses on content variables and their possible interaction with system variables, the interaction effects between system variables alone (e.g. stereoscopy and screen size) will not be discussed here. For more details refer to Kalisperis et al. (2006) and Zikic (n/d).

5.1 *Depth* estimation

Depth estimation	**High Level Realism**	**Low Level of Realism**
Wide FoV	M=1.37	**M=1.20**
Narrow FoV	M=1.24	M=1.25

Table 5.1 Interactive effect of FoV and level of realism on depth estimation

Depth estimation	**High Level of Detail**	**Low Level of Detail**
Big Screen	M=1.22	**M=1.16**
Small Screen	**M=1.20**	M=1.25

Table 5.2 Interactive effect of screen size and level of detail on depth estimation

The interaction between some of the variables had more interesting effects on spatial perception. For high level of detail, screen size did not make much difference in depth estimations, whereas for low level of detail results vary greatly between big screen and monitor. Although students overestimated depth in the high level of detail-condition whether they viewed it on the monitor or the large screen, they were more accurate in the low level of detail condition when looking on a large screen. Overestimation of depth for high detail condition regardless of screen size would be in line with Pinet's (1997) findings where participants perceived spaces with added furniture as larger. These objects most likely behaved as perceptual agents in such a way that the more objects are present in the scene, the larger space appears to be in order to accommodate them. In this case, students most likely perceived spaces with more furniture as less empty and thus, less confining. However, low-detail stimulus viewed on the monitor has led to greatest overestimation of depth. Lack of sufficient cues along with the absence of scale reference between the viewer and the viewed space which big screen provides may have resulted in the perception of space as being much larger.

The interaction between *field of view* and *level of realism* on depth perception showed that for one screen there was not much difference between low and high levels of realism as the depth estimation was similar in both instances. However, for three screens, level of realism had much more impact on depth estimations. The results indicate that when viewed on three screens, perceived depth was overestimated by a larger amount for high level of realism compared to low level of realism. These findings tend to suggest that added photorealism affected the perception of spaces in a way that led to amplified depth perception. Shadow affects the perception of space in such way that it makes the space appear larger. In addition to larger amount of spatial information provided by three screens, multiple light sources casting shadows in high realism condition could have further increased the sensation of depth in addition to other cues.

This again would be in line with assumptions that adding concordant depth cues might lead to an amplified perception of depth (Epstein, 1995). In this case, pictorial depth cues included in high realism condition (shadow, shade, texture) appears to have cumulative effect on the depth perception. This might suggest that photorealism may not the best method for dimensional evaluation of spaces. It may be better suited for the qualitative evaluation of spaces and the feel of spaces.

5.2 The *width* estimation

Width estimation	**High Level Realism**	**Low Level of Realism**
Wide FoV	M=1.28	M=1.16
Narrow FoV	M=1.16	M=1.24

Table 5.3 Interactive effect of field of view and level of realism on width estimations.

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For estimating width, results suggest that when displayed in the wide field of view, low realism had equally accurate estimations as the high realism for the narrow field of view. Conversely, high realism displayed on wide field of view and low realism displayed on narrow field of view both resulted in greater overestimation of width. Similarly to depth estimates, the explanation could be that high realism combined with the wide field of view provided much more spatial information and greater number of cues whose combined effect resulted in overestimation of width. On the other hand, low realism displayed on one screen (narrow field of view) most likely lacked sufficient spatial information and depth cues. Both conditions however, for different reasons resulted similarly with the greater overestimation of width. Depending on the task at hand and desired effect, this fact should be taken into consideration when deciding on the level of information to be displayed.

5.3 The *height* estimation

Height estimation	Stereo	Mono
Big screen	M=1.23	M=1.13
Small screen	M=1.11	M=1.10

Table 5.4 Interactive effect of screen size and stereoscopy on height estimation

Height estimation	Stereo	Mono
High Level of Detail	M=1.20	M=1.10
Low Level of Detail	M=1.11	M=1.10

Table 5.5 Interactive effect of stereoscopy and level of detail on height estimation

When it comes to height estimation, in non-stereo condition there was not much difference between low level and high levels of detail as the estimates in both cases were equally accurate. On the other hand, when viewed in stereo high level of detail resulted in a greater overestimation compared to low level of detail. Given the fact that most objects and structures are of standardized height, it was expected that more objects of known size would provide more information for height estimations. Nonetheless, compared to depth and width estimates, height estimations were far closer to being accurate except in high detail and stereo condition where height was greatly overestimated. Since both low and high level of detail viewed as mono had highly accurate height estimations, it seems as the stereo display affected the perception of objects in a way that it enlarged their appearance. One possibility could be that stereo parameters were not accurate enough or inconsistent in terms of the objects-user or the user-display scale relations. This possible inaccuracy might have been accentuated by more objects being present in the scene resulting in a more severe distortion of the objects' height.

One suggestion for further research might be adding other elements such as human figures of known size. It is possible that architectural details alone did not offer sufficient cues of scale.

5.4 *Spatial organization*

Spatial organization	Stereo	Mono
Big screen	M=8.44	M=6.46
Small screen	M=8.22	M=7.95

Table 5.6 Interactive effect of screen size and stereoscopy on spatial organization

Spatial organization	Stereo	Mono
High Level of Detail	M=6.30	M=8.62
Low Level of Detail	M=7.95	M=8.22

Table 5.7 Interactive effect of stereoscopy and level of detail on spatial organization

Results for spatial organization reveal that participants had developed much better cognitive map when viewing the model in mono regardless of level of detail. On the other hand, participants in stereo condition had a less clearer cognitive map when viewing high detail model compared to low detail. One possibility is that high detail might have had a distracting effect, forcing the user to focus more on objects than spaces. Similarly to height estimations, it is also possible that stereo parameters were inaccurate, making it harder for the viewer to focus on spaces. However, further research is needed before making general conclusions.

There are also issues about the model that should be taken into consideration. The relatively open floor plan for the model was chosen primarily to allow for more spatial information during the walkthrough, given the confining nature of a common residence. If more walls were used to separate spaces, the field of view would be narrowed further making the walkthrough less smooth. However, the open floor plan has its drawback in that it allows the participant to see more than one space at the time. This may have consequences on the attention that might be drawn away from the space in focus, or as another form of information clutter and overload.

The problem of having an open floor plan was often reflected in the inability to distinguish the boundaries of open spaces in the labeling and proportioning tasks. Proportioning part, although statistically not significant, was interestingly often contradicting participants' sense of the sizes of spaces when the task was to rank them from the smallest to the biggest space. Although many a times had a perfect sense of the relation between spaces in terms of their sizes, participant would fail to translate that information onto a plan. This would be in line with Henry's (1992) observations that imprecision in spatial organization may not necessarily be due to participants' inability to build an accurate cognitive map but the inability to translate the map onto plan even when the mental map is actually accurate. This suggests that the method adopted for assessing one's perception about spatial proportions is not quite accurate and better methods need to be developed. In any event, the proportioning task in this study failed to show any significant differences between conditions.

5.5 The *level* and the *ease of immersion*

Level of immersion	**High Level of Detail**	**Low Level of Detail**
3 screens	M=5.21	M=4.90
1 screen	M=4.40	M=5.37

Table 5.8 Interactive effect of field of view and level of detail on level of immersion

Level of immersion	**Stereo**	**Mono**
Big screen	M=5.56	M=4.47
Small screen	M=5.44	M=5.29

Table 5.9 Interactive effect of screen size and stereoscopy on level of immersion

Level of immersion	**Stereo**	**Mono**
High Level of Detail	M=3.90	M=4.91
Low Level of Detail	M=5.44	M=5.29

Table 5.10 Interactive effect of stereoscopy and level of detail on level of immersion.

The results on the level of immersion in terms of “being in the house”, “grasping an object”, or “how real the object felt”; confirmed the general expectation that the bigger screen and stereoscopy would induce the greater level of immersion. There is however are interesting interactive effects between the detail and the field of view, as well as level of detail and stereoscopy.

The interaction between level of detail and field of view showed that for three screens, level of immersion was equally high for both high and low level of detail. On the other hand, in one screen condition, level of immersion was much more affected by level of detail. In contrast to higher level of immersion in low detail condition, the increased level of detail actually lowered the level of immersion. This suggests that wide field of view positively affects level of immersion regardless of level of detail. On the other hand, for one screen, level of detail has a prevailing effect on level of immersion.

Somewhat similar are the results on the interactions occur between detail and stereoscopy. Low level of detail in both non-stereo and stereo condition had resulted in the higher level of immersion than the high level of detail. Further, high detail had more positive effect on the level of immersion in non-stereo condition compared to stereo. This shows the trend where the increase of visual stimuli affected the level of immersion causing its decrease.

The effect that level of detail had on the level of immersion in both abovementioned cases may be explained by the fact that architecture students rarely use such additional and decorative objects that were used in this model for creating and evaluating designs. It might be that in this case they were very sensitive and thus very aware of their “artificiality”. Although in reality, objects like furniture and decoration contribute to the dimension of complexity, in this case even if all these elements were represented faithfully the effect would not necessarily be similar to reality.

Ease of immersion	High Level Realism	Low Level of Realism
3 screens	M=6.74	M=6.61
1 screen	M=6.50	M=5.55

Table 5.11 Interactive effect of field of view and level of realism on ease of immersion

Ease of immersion	Big screen	Small screen
3 screens	M=6.05	M=6.61
1 screen	M=5.80	M=5.55

Table 5.12 Interactive effect of field of view and screen size on ease of immersion

As for the ease of immersion, the findings would agree with numerous observations from the studies discussed earlier (Lombard & Ditton, 1997; IJsselsteijn, 2000). Wide field of view resulted in easier immersion regardless of level of realism. On the other hand, for one screen condition, high realism had much more positive impact on ease of immersion compared to low level of realism. Participants felt that they were more easily immersed in wide field of view and highly realistic environment, compared to low realism and narrow field of view.

Before drawing conclusions on immersion, it is important to keep in mind that in this study the user could neither interact with the model, nor was there any kinesthetic feedback. These are factors which are stated to be important for the sense of presence. Presence is a very complex phenomenon and there might be other factors that might have contributed to presence but were not measured. The possibility of user interaction would have contributed more to the feeling of being immersed thus increasing the sense of presence. In addition, in an animated walkthrough motion realism is as important as the visual realism since even slightly inappropriate motion might distract the user from the intended experience according to Diefenbach (1994). Although the speed and the camera movement strived to match as close as possible walking in the real world, there is a possibility that the six minute long walkthrough might have been exasperating for the participant who was in the role of a passive observer.

5.6 Limitations

Since this was a screening experiment, the main interest was to reveal and establish some trends given the limited subject pool resulting in less statistical power. This shortcoming is expected to be resolved once the second wave of data collection is done. This will also enable further exploration of the role of presence as a possible mediator of the effects of the system variables on spatial cognition.

There are inherent limitations in the VR system used for this experiment in terms of both hardware and software. This was primarily reflected in a tradeoff between the smoothness of movement and visual quality of the stimulus which was further emphasized when rendered for the wide field of view and the narrow field of view. Compromise had to be made by lowering the image resolution for all conditions in order to ensure consistent frame rates and to enable smooth motion. Due to a limitation of the software used for playing movies, the duration of the movie rendered in 3:1 ratio for the three-screen condition was initially twice as long as the same movie rendered for one screen. Therefore, the image resolution for the three-screen condition was lowered even further in order to match the duration of the animation in all conditions. This resulted in a more visible pixilation of the displayed image in all three-screen conditions, especially when displayed on big screens.

Another thing that came to attention is the overlap of two independent variables – level of detail and field of view. Since level of detail was operationalized as the number of depth cues by means of functional objects and details in the scene, in the wide screen condition this number may have increased at certain key stops including additional elements, thus providing additional depth cues. Furthermore, the perspective on one-screen image is not fully isomorphic with the perspective on three-screen image. This creates a difficulty in interpreting the results where the widescreen display made a significant difference. It cannot be concluded whether the variation was caused by a difference in perspective or whether it resulted from additional cues.

Projection screens used for the experiment were also limiting in terms of truthfully displaying colors and illumination compared to the monitor. The image appeared slightly darker with less distinguishable colors. Images in high realism were thus perceived as even darker due to the number of shadows used in the model. These issues need to be taken into consideration for the future research.

5.7 Overall conclusion

With the rapid development of VR technology and its increasing popularity in the field of architecture, it is becoming more common to consider using VR to evaluate spaces before they are built. This research started with the intention to contribute to the knowledge of how VR can augment and aid spatial perception and cognition that are critical components of the design thinking. The study here did identify some trends about evaluation of spaces. The results presented here demonstrated the students' general tendency to overestimate distances in VR in all conditions. The question is what would be then the best configuration to use for the evaluation of designed spaces? The answer would be that it depends on the task at hand and the context of VR utilization. More specifically, in the context of the design studio, for evaluation of spaces in terms of size and scale, this study confirms the usefulness of having large screen and wide field of view due to the fact that they provide a scale reference and sufficient spatial information. At the same time, when using big screen and wide field of view, detail and realism should be kept at low levels. An overview of results showed that detail and realism had more impact on the spatial cognition depending on whether they were displayed on the monitor or a big screen, narrow or wide field of view, or in stereo and non-stereo mode. If however, the context of use was for a presentation to a client, a useful and affordable combination would be to display a highly detailed and highly realistic model on a small screen with a narrow field of view.

Reported results point out to the need for appropriate combination of the content and display variables when the task is the dimensional assessment of spaces. It seems that low levels of detail and realism had to counterbalance the level of spatial information provided by large screen and wide field of view in order to make more accurate estimations. One solution might be including fewer elements of scale. On the other hand, in the context of design studio detail and realism may not be the best tool for making quantitative judgments of spaces, but might be better suited for the qualitative evaluation of the design at later stages of design and possibly a better way for experiencing the intended reality.

Although stereoscopy is one of the valued aspects of VR technology, the results suggest that stereoscopy may hinder making quantitative judgments. Here, non-stereo came up as being more effective regardless of other content variables. If stereo environment is used in a task for assessing spatial dimensions, it should have low level of detail. One suggestion for future research is to give more attention and care to stereo parameters such as eye separation and determine if and how the scale difference between small and large display might have required different calibration of these parameters. The lack of known correspondence between the dimensions of the virtual world and the real world conditions of the viewer and the real world space occupied makes more difficult to observe the big screen / small screen differences in estimation of spatial relationships among stereo views.

To conclude, this study confirmed some of the assumptions stated earlier that the accuracy in depth estimations and dimensioning tasks vary with different depth cues. Furthermore, findings of this study also highlighted the complexity of the research question and multi-dimensionality of VR as a system and its components. Nevertheless, despite its limitations, VR offers a range of opportunities for designers. It allows for new insights to designs through enhanced exploration.

5.8 Future research

In regard to the findings of this study and above discussed issues, the follow up study of Immersive Environments research group intends to explore other factors of interest such as screen resolution, luminosity, object-centric and viewer-centric representation and interactivity. Interaction may be interesting to explore from the point of view of better understanding of the spaces and their sizes by providing feedback along with the visual spatial information. Another area that might benefit from further investigation is identifying the differences among various groups such as between design majors and non-design majors, students and professionals. This might show whether VR can be used to bridge any gap that might exist between them.

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APPENDIX A

THE IRB APPROVAL

ORP USE ONLY: IRB#22310 Doc.#1
The Pennsylvania State University
Office for Research Protections
Approval Date: 02/02/06 JKG for DWM
Expiration Date: 01/23/07 JKG for DWM
Social Science Institutional Review Board

INFORMED CONSENT FORM FOR SOCIAL SCIENCE RESEARCH
The Pennsylvania State University

Title of Project: Effect of virtual reality system variables on architectural design comprehension

Principal Investigator: Loukas N. Kalisperis
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1. Purpose of the Study: The purpose of the project is to identify which virtual reality system variables make a significant impact on architectural design comprehension and in creating a sense of presence.

2. Procedures to be followed: You will be presented with a series of computer images of a building on the display screens in the Immersive Construction Lab (iCon lab). You will be asked to complete a

questionnaire which would have questions pertaining the space /building you were shown such as to estimate the size of the room, which rooms are adjacent to each other, etc.

3. Discomforts and Risks: There are no risks in participating in this research beyond those experienced in everyday life.

4. Benefits:
   a. You might learn more about architectural presentation using virtual reality.
   b. This research might provide a better understanding of how each of the virtual reality system components such as screen size, stereoscopy etc affect ones understanding of architectural.

5. Duration: It will take about 30 - 40 minutes to complete the study.

6. Statement of Confidentiality: Only the person in charge, and his/her assistants, will know your identity. If this research is published, no information that would identify you will be written. Your name will not be associated with any of the data collected in any manner. Only the principal investigator and the co-investigators will have access to the data collected and the data would be stored securely in a locked file cabinet in the co-investigator's office.
   The following may review and copy records related to this research:
   - The Office of Human Research Protections in the U.S. Department of Health and Human Services
   - Penn State University's Social Science Institutional Review Board
   - Penn State University's Office for Research Protections

7. Right to Ask Questions: You can ask questions about the research. The person in charge will answer your questions. Contact Loukas Kalisperis at 865-0877 or Bimal Balakrishnan at 814-777-0616 with questions. If you have questions about your rights as a research participant, contact Penn State's Office for Research Protections at (814) 865-1775.

8. Compensation: There is no compensation for the study and participation is completely voluntary. You may withdraw your participation at anytime without penalty.

9. Voluntary Participation: You do not have to participate in this research. You can end your participation at any time by telling the person in charge. You do not have to answer any questions you do not want to answer.

You must be 18 years of age or older to consent to participate in this research study. If you consent to participate in this research study and to the terms above, please sign your name and indicate the date below.

You will be given a copy of this consent form to keep for your records.

_______________________________ Participant Signature   _______________ Date

_______________________________ Investigator Signature   _______________ Date

Page 2 of 2

APPENDIX B

THE STIMULUS

Key Stops


Stop 1 - Exterior


Stop 2 – Living room


Stop 3 – Dining room


Stop 4 - Kitchen


Stop 5 – Study room


Stop 6 – Hallway

High Realism and Low Realism


1


2


3

4

5

6

High Detail and Low Detail

1

2

3

4

5

6

One Screen and
Three Screens

APPENDIX C

THE QUESTIONNAIRE

Subject No.______________

SS	NoS	D	R	Str

Please do not write in this box

GENERAL INFORMATION

1. Age

☐ years

2. Gender

☐ Male ☐ Female

3. Height

Height ☐ ft - ☐ in

4. Academic Major

☐

5. Academic Standing

☐ 1st year
☐ 2nd year
☐ 3rd year
☐ 4th year
☐ 5th year
☐ Other If other, please specify ☐

When you have finished the section, **NOTIFY** the research assistant.
Please **DO NOT** proceed to the next section until the research assistant asks you to.

Subject No.______________				
SS	NoS	D	R	Str
Please do not write in this box				

IMMERSIVE ENVIRONMENTS LABORATORY RESEARCH

Thank you for your help to make this research a success! Your participation will help us improve the Immersive Environments Laboratory now being built in the new School of Architecture and Landscape Architecture, the Stuckeman Family Building.

SECTION 1

Based on the presentation you just saw, please mark your answer to the following question by circling a number on a scale 1 to 8.

1. To what extent did you feel you *were* physically in the house?

Not at all	1	2	3	4	5	6	7	8	A great deal

2. To what extent was it easy for you to get used to the house?

Not at all	1	2	3	4	5	6	7	8	A great deal

3. To what extent did you have to pay a lot of attention about what was going on in the house?

Not at all	1	2	3	4	5	6	7	8	A great deal

4. To what extent did you feel that what you saw in the house was similar to reality?

Not at all	1	2	3	4	5	6	7	8	A great deal

Please **PROCEED** to the next page.

Subject No.________________				
SS	NoS	D	R	Str

Please do not write in this box

5. How easy was it for you to get a good feel of the spaces in the house?

Not at all	1	2	3	4	5	6	7	8	Very easy

6. How much did your experience in the house seem consistent with your real world experience?

Not at all	1	2	3	4	5	6	7	8	A great deal

7. How compelling was your sense of moving around inside the house?

Not at all	1	2	3	4	5	6	7	8	A great deal

8. How realistic did the house appear to you?

Not at all realistic	1	2	3	4	5	6	7	8	Highly realistic

9. To what extent did you feel you could reach into the house and grasp an object?

Not at all	1	2	3	4	5	6	7	8	A great deal

10. To what extent did the objects appear to be properly sized relative to other objects?

Not at all	1	2	3	4	5	6	7	8	A great deal

Please **PROCEED** to the next page.

Subject No.________				
SS	NoS	D	R	Str

Please do not write in this box

11. How real did the objects in the house appear to you?

Not at all realistic	1	2	3	4	5	6	7	8	Highly realistic

12. To what extent did you feel you *went int*o the house?

Not at all	1	2	3	4	5	6	7	8	A great deal

13. To what extent did the experience require a mental effort from you?

Not at all	1	2	3	4	5	6	7	8	A great deal

When you have finished the section, **NOTIFY** the research assistant.
Please **DO NOT** proceed to the next section until the research assistant asks you to.

Subject No.________________				
SS	NoS	D	R	Str

Please do not write in this box

SECTION 2

1. The height of the highest roof point of the house excluding the chimney.

- ☐ 19 ft
- ☐ 21 ft
- ☐ 25 ft
- ☐ 29 ft
- ☐ 31 ft

2. The shortest horizontal distance from the SUV to the foot of the chimney.

- ☐ 22 ft
- ☐ 26 ft
- ☐ 30 ft
- ☐ 34 ft
- ☐ 38 ft

3. The overall width of the house.

- ☐ 37 ft
- ☐ 41 ft
- ☐ 45 ft
- ☐ 49 ft
- ☐ 53 ft

Please **PROCEED** to the next page.

Subject No.______________				
SS	NoS	D	R	Str

Please do not write in this box

4. The length of the path from the sidewalk to the door.

- ☐ 22 ft
- ☐ 26 ft
- ☐ 30 ft
- ☐ 34 ft
- ☐ 38 ft

5. How many footsteps would it take you to get from the sidewalk to the door?

- ☐ 3 - 7
- ☐ 8 - 12
- ☐ 13 - 17
- ☐ 18 - 22
- ☐ 23 - 27

When you have finished the section, **NOTIFY** the research assistant.
Please **DO NOT** proceed to the next section until the research assistant asks you to.

Subject No.______________				
SS	NoS	D	R	Str

Please do not write in this box

SECTION 3

6. How well furnished do you think the LIVING ROOM is?

Not at all furnished	1	2	3	4	5	6	7	8	Highly furnished

7. Estimate the dimensions of the LIVING ROOM. Please round off dimensions to the nearest 3 inches.

Width [ft] - [in]

Height [ft] - [in] (up to the beginning of the ceiling slope)

Mark the difficulty to estimate the dimensions of the **LIVING ROOM**:

Easy to estimate	1	2	3	4	5	6	7	8	Difficult to estimate

8. How many people do you think can be in the LIVING ROOM without feeling crowded if all of them are standing?

- [ ] 3 - 7
- [ ] 8 - 12
- [ ] 13 - 17
- [ ] 18 - 22
- [ ] 23 - 27

Estimate the following. Please round off dimensions to the nearest 3 inches.
9. The width and height of the shelf.

Width [ft] - [in]

Height [ft] - [in]

Please **PROCEED** to the next page.

Subject No.________________				
SS	NoS	D	R	Str

Please do not write in this box

10. The shortest distance between the shelf and the coffee table.

Distance [ft] - [in]

11. The shortest distance between the coffee table and the fireplace.

Distance [ft] - [in]

12. The shortest distance between the fireplace and the perpendicular outside wall.

Distance [ft] - [in]

13. How photorealistic do you think the LIVING ROOM is?

Not at all realistic	1	2	3	4	5	6	7	8	Very realistic

When you have finished the section, **NOTIFY** the research assistant.
Please **DO NOT** proceed to the next section until the research assistant asks you to.

Subject No.________________				
SS	NoS	D	R	Str

Please do not write in this box

SECTION 4

14. Estimate the dimensions of the DINING ROOM. Please round off dimensions to the nearest 3 inches.

Width [ft] - [in] (total - wall to wall)

Height [ft] - [in]

Mark the difficulty to estimate the dimensions of the **DINING ROOM**:

Easy to estimate	1	2	3	4	5	6	7	8	Difficult to estimate

15. How many people do you think can sit at the dining table?

- [ ] 1 - 3
- [ ] 4 - 6
- [ ] 7 - 9
- [ ] 10 - 12
- [ ] 13 - 15

Estimate the following. Please round off dimensions to the nearest 3 inches.
16. The width and length of the dining table.

Width [ft] - [in]

Lenght [ft] - [in]

17. The shortest distance between the dining table and the kitchen entrance.

Distance [ft] - [in]

Please **PROCEED** to the next page.

Subject No.______________

SS	NoS	D	R	Str

Please do not write in this box

18. The shortest distance between the dining table and the shelf.

Distance [ft] - [in]

When you have finished the section, **NOTIFY** the research assistant.
Please **DO NOT** proceed to the next section until the research assistant asks you to.

Subject No.______________				
SS	NoS	D	R	Str

Please do not write in this box

SECTION 5

19. How well furnished do you think the KITCHEN is?

Not at all furnished	1	2	3	4	5	6	7	8	Highly furnished

20. Estimate the dimensions of the KITCHEN. Please round off dimensions to the nearest 6 inches.

Width [ft] - [in]

Depth [ft] - [in]

Height [ft] - [in]

Mark the difficulty to estimate the dimensions of the **KITCHEN**:

Easy to estimate	1	2	3	4	5	6	7	8	Difficult to estimate

Estimate the following. Please round off dimensions to the nearest 3 inches.
21. The height of the breakfast counter.

Height [ft] - [in]

22. The height of the fridge.

Height [ft] - [in]

23. The shortest distance between the fridge and the oven.

Distance [ft] - [in]

Please **PROCEED** to the next page.

Subject No.______________				
SS	NoS	D	R	Str

Please do not write in this box

24. How photorealistic do you think the KITCHEN is?

Not at all realistic	1	2	3	4	5	6	7	8	Very realistic

When you have finished the section, **NOTIFY** the research assistant.
Please **DO NOT** proceed to the next section until the research assistant asks you to.

Subject No.______________				
SS	NoS	D	R	Str

Please do not write in this box

SECTION 6

25. Estimate the dimensions of the STUDY ROOM. Please round off dimensions to the nearest 3 inches.

Width [ft] - [in] (up to the stairs)

Height [ft] - [in]

Mark the difficulty to estimate the dimensions of the **STUDY ROOM**:

Easy to estimate	1	2	3	4	5	6	7	8	Difficult to estimate

26. How many people do you think can be in the STUDY ROOM without feeling crowded if all of them are standing?

- [ ] 3 - 7
- [ ] 8 - 12
- [ ] 13 - 17
- [ ] 18 - 22
- [ ] 23 - 27

Estimate the following. Please round off dimensions to the nearest 3 inches.
27. The height of the stair landing from the floor level.

Height [ft] - [in]

28. The depth of the laundry room.

Depth [ft] - [in]

Please **PROCEED** to the next page.

Subject No.______________				
SS	NoS	D	R	Str

Please do not write in this box

29. Rank each space from the smallest size to the largest one. Attribute a 1 to the smallest, a 2 to the next largest and so on. If two spaces are the same size in square footage, give each one the same value.

LIVING ROOM	
DINING ROOM	
KITCHEN	
STUDY ROOM	

When you have finished the section, **NOTIFY** the research assistant.
Please **DO NOT** proceed to the next section until the research assistant asks you to.

Subject No.________________				
SS	NoS	D	R	Str

Please do not write in this box

SECTION 7

Estimate the following.

30. The width of the HALLWAY between the MASTER and GUEST bedroom on the second floor.

- ☐ 2 ft – 6 in
- ☐ 3 ft – 0 in
- ☐ 3 ft – 6 in
- ☐ 4 ft – 0 in
- ☐ 4 ft – 6 in

31. The distance between the doors of the MASTER and GUEST bedroom on the second floor.

- ☐ 9 ft – 6 in
- ☐ 10 ft – 0 in
- ☐ 10 ft – 6 in
- ☐ 11 ft – 0 in
- ☐ 11 ft – 6 in

32. How many footsteps would it take you from the MASTER bedroom door to the GUEST bedroom door?

- ☐ 1 - 2
- ☐ 3 - 4
- ☐ 5 - 6
- ☐ 7 - 8
- ☐ 9 - 10

When you have finished the section, **NOTIFY** the research assistant.
Please **DO NOT** proceed to the next section until the research assistant asks you to.

Subject No.______________

SS	NoS	D	R	Str

Please do not write in this box

SECTION 8

33. Which space is below the MASTER bedroom on the second floor?

- [ ] rest room
- [ ] study room
- [ ] laundry
- [ ] living room
- [ ] dining room

34. Which space on the second floor is above the KITCHEN?

[ ]

35. Which space is below the GUEST bedroom on the second floor?

- [ ] rest room
- [ ] study room
- [ ] dining room
- [ ] kitchen
- [ ] living room

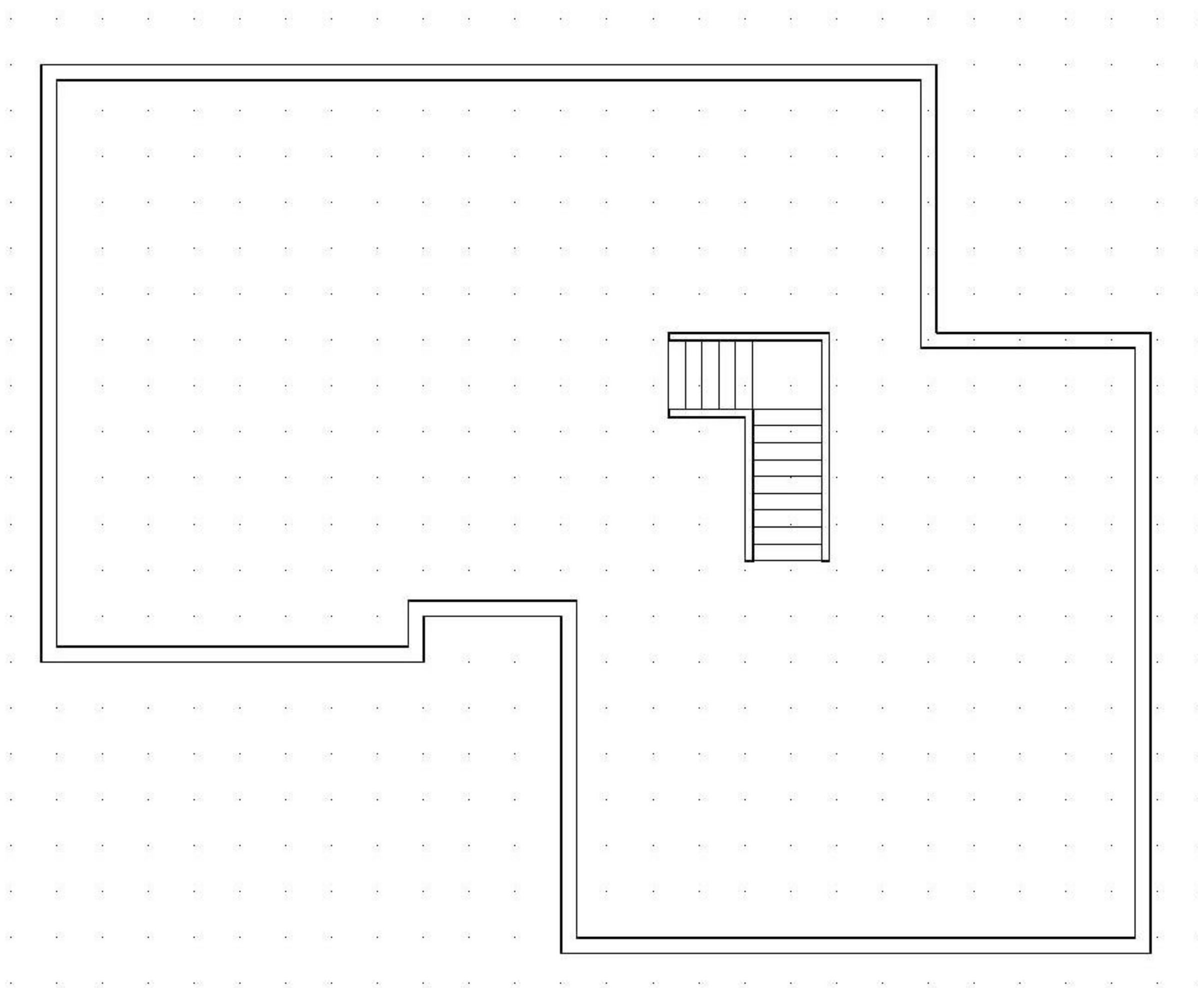
Please **PROCEED** to the next page.

Subject No.______________				
SS	NoS	D	R	Str

Please do not write in this box

36. On the sketch of the first floor plan shown below draw the OUTLINES of the spaces the way they are organized and LABEL them.

KITCHEN	LIVING ROOM	MAIN ENTRANCE
STUDY ROOM	GARAGE	REST ROOM
DINING ROOM	LAUNDRY	



37. On the sketch of the first floor plan shown above draw a line showing the PATH of your visit through the spaces. Place ARROWS on the line to show the direction of movement.

When you have finished the section, **NOTIFY** the research assistant.
Please **DO NOT** proceed to the next section until the research assistant asks you to.

Subject No.________________				
SS	NoS	D	R	Str

Please do not write in this box

SECTION 9

1. Have you used the Immersive Environments Lab (IEL) before?

☐ yes
☐ no

If NO, please skip to question 2.

a. If yes, how often did you use the Immersive Environments Lab (IEL) before?

Very rarely	1	2	3	4	5	6	7	8	Very often

b. If yes, how would you rate your experience with the Immersive Environments Lab (IEL)?

Very poor	1	2	3	4	5	6	7	8	Very good

c. If yes, how was your overall comfort level in using the technology in the Immersive Environments Lab (IEL)?

Not at all comfortable	1	2	3	4	5	6	7	8	Highly comfortable

Please **PROCEED** to the next page.

Subject No.______________				
SS	NoS	D	R	Str

Please do not write in this box

2. Estimate the average hours per week during this term that you spent using the computer for course related activities.

This term, on average I spent [ ] hours per week using a computer on all course related activities.

3. Estimate the average hours per week during this term that you spent using the computer for personal or leisure related activities.

This term, on average I spent [ ] hours per week using a computer for personal or leisure related activities.

4. Estimate your experience with 2D-graphics software in general (Photoshop, Illustrator, InDesign, QuarkExpress, etc).

I have [ ] months experience in using 2D-graphic design software.

5. Estimate your experience with 3D-modelling with computer aided design software in general (Form.Z, AutoCAD, SketchUp, 3DStudio Max, etc).

I have [ ] months experience in 3D-modelling with computer aided design software.

THANK YOU for taking the time to complete the questionnaire. We need and value your participation in our research to make the future Immersive Environments Lab even better!

APPENDIX D

EXPERIMENT PROTOCOL

ONE DAY BEFORE

1. Send e-mail reminders to the subjects for the following day
    a. Include directions to the IEL (in room 306 Eng Unit C between Hammond and Alumni Center)
    b. Include phone number

ON THE DAY OF THE STUDY

1. Go there half an hour early
2. Put the schedule list outside and put the sign outside on the door
3. Check the signs and directions
4. Bring enough questionnaires for that day
5. Bring a small calendar all the time for rescheduling
6. Bring pencils, reading lamp, refreshments
7. Unhook the lab phone
8. Check the runs for that day
9. Check all the equipment needed for the experiment that day
    a. Console
    b. Stand by machine
    c. Screens (projectors and filters on each screen)
    d. Stereo glasses
10. Check for the files for the conditions that day
11. Play the movie for the adequate condition and check for bugs
12. Write the conditions' code and the subjects' numbers for the day
13. In STEREO CONDITION – blindness test
14. Greet and brief the subject
15. Remind the subject to switch off the cell phone
16. Ask the subject to read and sign both copies of the consent form
    a. File one copy and give the other one to the subject
17. Seat the subject where he/she is suppose to be seated
18. Play the movie once for the presence section 1
19. Wait for the subject to fill up the questions in section 1
20. Play the part 1 of the movie
21. Ask the subject to fill up the questions in section 2
22. Repeat the step 20 and 21 for the remainder of the questionnaire
23. Thank the subject for the participation in the study
24. Ask for confidentiality
25. Offer refreshments
26. File the filled up questionnaires
27. Turn off all the equipment
28. Check the schedule for the next day of study and prepare