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CHARACTERISTICS OF HEAD MOUNTED DISPLAYS AND THEIR EFFECTS ON SIMULATOR SICKNESS

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ABSTRACT

Characteristics of head-mounted displays (HMDs) and their effects on simulator sickness (SS) and presence were investigated. Update delay and wide field of views (FOV) have often been thought to elicit SS. With the exception of Draper et al. (2001), previous research that has examined FOV has failed to consider image scale factor, or the ratio between physical FOV of the HMD display and the geometric field of view (GFOV) of the virtual environment (VE). The current study investigated update delay, image scale factor, and peripheral vision on SS and presence when viewing a real-world scene. Participants donned an HMD and performed active head movements to search for objects located throughout the laboratory. Seven out of the first 28 participants withdrew from the study due to extreme responses. These participants experienced faint-like symptoms, confusion, ataxia, nausea, and tunnel vision. Thereafter, the use of a hand-rail was implemented to provide participants something to grasp while performing the experimental task. The 2X2X2 ANOVA revealed a main effect of peripheral vision, $F(1,72) = 6.90$, $p = .01$, indicating peak Simulator Sickness Questionnaire (SSQ) scores were significantly higher when peripheral vision was occluded than when peripheral vision was included. No main effects or interaction effects were revealed on Presence Questionnaire (PQ version 4.0) scores. However, a significant negative correlation of peak SSQ scores and PQ scores, $r(77) = -.28$, $p = .013$ was revealed. Participants also were placed into 'sick' and 'not-sick' groups based on a median split of SSQ scores. A chi-square analysis revealed that participants who were exposed to an additional update delay of ~200 ms were significantly more likely to be in the 'sick' group than those who

were exposed to no additional update delay. To reduce the occurrence of SS, a degree of peripheral vision of the external world should be included and attempts to reduce update delay should continue. Furthermore, participants should be provided with something to grasp while in an HMD VE. Future studies should seek to investigate a critical amount of peripheral vision and update delay necessary to elicit SS.

DEDICATION

My first dedication is to the one man I respect and look up to the most in this world and who has sacrificed so much for my benefit, my father. You were always there. Words cannot adequately describe the immeasurable respect and admiration I have for you, nor how proud I am to be your son. One day I hope to be half the man and father you are. I also dedicate this, as well as everything I do, in the loving memory of my mother, who I know, along with my father, has given me the strength to persevere through every challenge life has presented thus far. I love you Mom and Dad.

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CHAPTER I

INTRODUCTION

The purpose of the present study was to examine multiple characteristics of head/helmet-mounted displays (HMDs) and their effects on simulator sickness (SS) and presence. The overarching goal was to expand the current research that attempts to answer the underlying question, “What characteristics of HMDs make people sick?” A secondary goal of the current study was to examine the relationship, if any, between presence and SS.

HMDs are visual displays (usually, liquid crystal displays; LCDs) worn on the head that include a head tracking system to provide user’s head orientation and location information to a computer (Blade & Padgett, 2002). HMDs are used to display virtual environments (VEs) for the purposes of training and simulation, or entertainment. VEs are often used to train highly skilled professionals, such as naval aviators. It is advantageous to train such professionals using VEs for numerous reasons. Foremost, is that training applications can be simulated without exposing these professionals to the harm of real-life consequences of injury, or even mortality, due to poor performance or low skill. A further description of VEs and HMDs will follow in subsequent sections.

The use and advantages of VEs do not come without their potential drawbacks. Individuals may develop motion sickness (MS)-like symptoms due to their exposure in VEs. These symptoms have become to be known as simulator sickness (SS) or cybersickness. Briefly, SS was initially used to described the MS-like symptoms that were observed from exposure to flight simulators (Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1989). Cybersickness is similar to the symptoms of SS and thus the terms SS and cybersickness has often been used interchangeably. The primary difference is that SS was initially used to describe the symptoms arising from simulators, whereas cybersickness refers to the symptoms occurring from exposure to other types of VEs, most predominately HMD VEs (Stanney, Kennedy, & Drexler, 1997).

As car-sickness, sea-sickness, space-sickness, and others are all subsets of MS, so is cybersickness a subset of SS. Regardless if sickness symptoms are provoked by natural or artificial stimuli, MS is the overarching phenomenon with all other subsets denoting the environment "where" MS occurred. Specific environments can evoke unique predominate symptoms, such as eye-strain with SS. Maximal, or the most severe MS will eventually result in emesis, regardless of environment.

The current research examined the effects of three characteristics of HMDs on SS and presence, specifically: update delay, image scale factor as manipulated by geometric field of view (GFOV), and a physical aspect of the HMD. Update delay and image scale factor are two display parameters of an HMD VE. The physical aspect of the HMD manipulated was peripheral vision. There are two differences between the current study and previous research. First, most of the previous research has examined the aforementioned characteristics using a VE, or in other words, an artificially computer generated scene. The current study had a more basic approach by utilizing a VE depicting a "real" visual scene captured by a video camera. Second, previous research has primarily focused on individual HMD characteristics, rather than on how these characteristics may interact.

CHAPTER II

PREVIOUS RESEARCH

Causes of Simulator Sickness

The Vestibular System and the Vestibular-Ocular Reflex

The two human sensory systems that are stimulated most often while in an HMD VE are the vestibular and visual systems. The vestibular system detects and provides information about head movements. One vestibular apparatus/organ is located in each inner ear. The main components of the vestibular organ are the semi-circular canals and the otoliths. See Figure 2.1. Semicircular canals (SCCs) detect angular accelerations of head movement, while the otoliths detect linear accelerations (Draper, 1996).

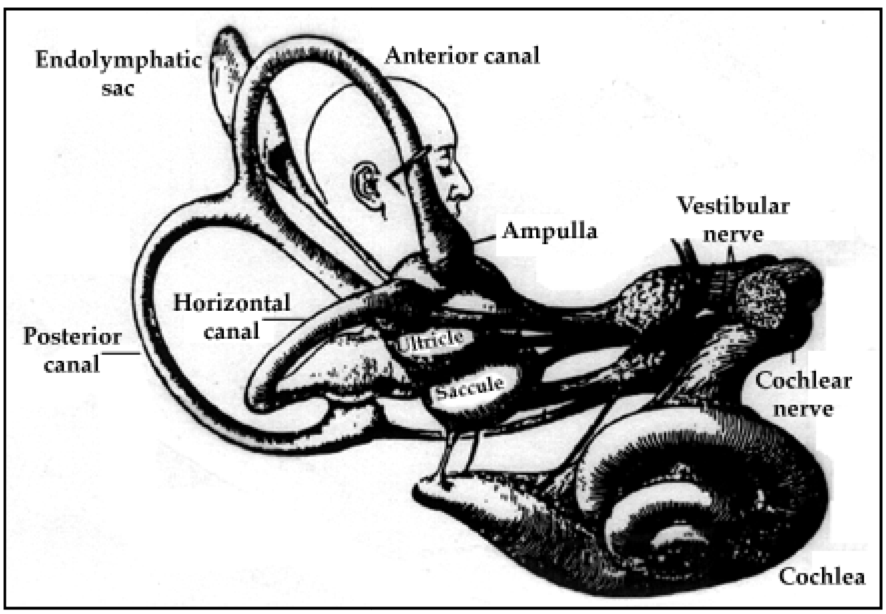

Figure 2.1. Diagram of the human vestibular apparatus (from Howard, 1986a, as cited in Draper, 1996).

The interaction of the ocular and vestibular systems is known as the vestibular-ocular reflex (VOR). The purpose of this eye-movement reflex is to maintain retinal image stabilization during head movements when an individual is focusing on an object (Sharpe & Johnston, 1993). The VOR accomplishes this by generating eye movements opposite in direction, but approximately equal in velocity as head movements (Sharpe & Johnston, 1993). For example, if individuals rotate their head to the left, their eyes will move to the right at the same rate as their head. If this were not to occur, such abilities as reading while walking would not be possible. Ideally, the VOR gain, or ratio of eye movement velocity/motion to head movement velocity/motion should be of unity, or 1 (Tabak & Collewijn, 1994). If gain deviates from 1, retinal image slip will begin to occur, with more severe slippage occurring with greater deviations from unity. Vestibular system input stimulates the VOR.

The input of the SCCs directs the VOR (Robinson, 1981). Angular head accelerations are detected by three pairs of SCCs, 3 SCCs in each ear (anterior, posterior, and horizontal canals). These pairs detect movement along each plane of motion and are termed “push-pull pairs” (Draper, 1996). Angular motion detection begins with the inertial force produced by the rotation of the head that causes endolymph fluid to bend the cupula of each SCC (Draper, 1996). The cupula is a flap that stretches across the ampula (enlarged area of each SCC), preventing endolymph fluid from flowing into the ampula (Draper, 1996). Tiny hair cells at the base of each cupula are then displaced and send signals to the brain. The brain perceives angular head acceleration by integrating the information provided by each “push-pull pair” of SCCs. If acceleration occurs in the plane of motion that the particular SCC is sensitive to, excitatory responses occur, whereas if the acceleration is in the opposite direction, the SCC sends inhibitory responses (Draper, 1996).

It has been reported that VOR compensatory eye movements in humans have latencies anywhere from 4-13 ms after onset of head movement (Johnston & Sharpe, 1994; Tabak & Collewijn, 1994; Collewijn & Smeets, 2000). This short response is attributed to the existence of very short neural connections between the vestibular and oculomotor systems (Collewijn & Smeets, 2000).

This latency contributes to the human perception of lag in visual stimuli. Human visual stimulus lag is the temporal differential between head movement and the onset of visual stimulus presentation. In natural environments, this lag can result from eye movements trailing behind head movements and the time to process the new visual scene/stimulus. For example, when individuals rotate their head to look to the left, the individuals' head will get there sooner than their eyes. As a result, the individuals do not "see" the visual scene instantaneously upon head movement "arrival." Naturally occurring lags are so small as to be rarely noticeable.

In VE research, specifically SS research, the role of the otoliths in the vestibular system is often overlooked. Usual movements that occur in HMD VEs, if any at all, are of angular head movements. Therefore, the role of the SSCs is often the predominate discussion point regarding motion perception within HMD VEs. Nonetheless, the stimulation, or lack of stimulation, of the otoliths is still important in motion perception within HMD VEs.

Otolith organs detect linear acceleration of the head and information on head tilt and other static head positions. There are two otolith organs in each vestibular apparatus, the utricle and the saccule. The receptor part of the utricle and saccule is the macula. When the head is tilted, or when linear acceleration takes place, the otoliths deform a gel-like substance covering the macula (Draper, 1996). This gel-like substance contains crystals of calcium carbonate called otoliths. The sheer force created by linear acceleration or head tilt bends and excites receptor hair cells in the macula (Draper, 1996). This signal is then transmitted via the 8^{th} cranial nerve to the vestibular nuclei (Draper, 1996). The utricle detects horizontal linear acceleration because the macula is located in the horizontal plane of the utricle (Robinson, 1981). The saccule detects vertical linear accelerations, including gravity because the macula is positioned vertically (Robinson, 1981).

Some HMD VE applications permit navigation along all or some planes of linear motion within the VE via a control device (e.g. joystick) even if the user remains stationary in the real-world. During these instances, the degree of linear motion detected by the otoliths is incongruent with the degree of linear motion perceived by the visual system.

The Sensory Conflict Theory of Motion Sickness

The most accepted theory of MS to date is Reason and Brand's (1975) sensory-conflict theory. The dominate symptoms of MS are nausea, vomiting, pallor, sweating, and to a lesser degree, salivary secretion and drowsiness (Reason & Brand, 1975). The sensory-conflict theory, sometimes termed sensory-mismatch theory, explains that the symptoms of MS arise due to conflicting motion information from sensory systems. These mismatches may occur due to two sensory systems providing conflicting motion cues simultaneously, or in some cases, current information from a sensory system conflicts with past experience as to what is to be expected in the current motion environment. Motion information provided by the visual system and the vestibular system may conflict and result in MS. These visual-vestibular mismatches are a key element of the sensory-conflict theory of MS (Reason & Brand, 1975). Some mismatches that may occur are when the vestibular system detects motion, while the visual system does not, and vice versa, or when both systems detect motion, but conflict with each other in degree of motion sensed. A simple example of visual-vestibular mismatch is MS that some people experience while reading in a car. The vestibular system detects both linear and angular motion, but the visual system fails to detect any motion, resulting in possible MS.

Although the sensory-conflict theory of MS, and subsets of MS, particularly SS in the current study, is widely accepted, other theories attempt to explain MS and SS. Two of the more popular theories are the postural instability (Riccio & Stoffregen, 1991) and eye-movement (Ebenholtz, 1992) theories.

Smooth pursuit, fixation, saccades, vestibular-ocular reflex (VOR), and optokinetic nystagmus (OKN) are several eye movements that respond to real or apparent motion (Flanagan, May, & Dobie, 2004). The eye movement theory of Ebenholtz (1992, as cited in Flanagan et al., 2004) suggests that these eye movements, when sustained, “function to stimulate cells within the vestibular nucleus, which then initiate vagal activity responsible for MS symptoms such as emesis (Flanagan et al., 2004, p. 337)." The fundamental basis for the eye movement theory (Ebenholtz, 1992; Ebenholtz, Cohen, & Linder, 1994) is that MS is not experienced by labyrinthine-defective individuals (Cheung, Howard, & Money, 1991) but labyrinthine-defective individuals have reported to experience vection (Ebenholtz, 1992). Therefore, Ebenholtz et al. (1994) "hypothesize that MS is to be understood not as a response to vestibular stimulation as such, but rather as a result of the eye movements controlled by the vestibular nuclei (p. 1032-1033)." The major downfall in the argument against an eye movement theory to MS is that it fails to explain how MS is experienced in blind people (Ebenholtz, 1992; Graybiel, 1970).

Succinctly, the postural instability theory suggests MS will persist in individuals who, when in an unstable environment, actively attempt to keep posture, whereas MS will lessen or cease to exist when individuals give in and posture is congruent to what the environment, real or virtual, affords (Riccio & Stoffregen, 1991). According to Riccio & Stoffregen (1991), postural instability is experienced first in the form of postural sway, and as a result, MS is elicited. However, the counter argument to this theory is that MS occurs in posturally neutral environments as well, such as in a car with car-sickness. Also, MS symptoms have been previously reported to not differ in a condition of postural restraint (lying down) as compared to free standing (Warwick-Evans, Symons, Fitch, & Burrows, 1998).

Flanagan et al. (2004) examined these three theories. Overall, results provided considerable evidence of sensory conflict factors having a greater role in the elicitation of MS than eye movement and postural instability factors (Flanagan et al., 2004). The only significant main effect was found with sensory conflict (moving and static visual scene). Scores on a MS symptom questionnaire were greater in all moving scene conditions as compared to static visual scene conditions. Although sensory conflict appeared to influence MS the most, contributions from eye movement and postural stability factors did occur in eliciting MS (Flanagan et al., 2004). As predicted, a significant three way interaction was revealed with the greatest amount of MS suggested in postural challenge, with moving visual scene without fixation (Flanagan et al., 2004).

These results suggested a possible effect of update delay on SS in the current study. It is plausible that update delay in HMD VEs contributes to a sensory conflict between vestibular information providing real motion sensation and the expected response in the visual scene, more specifically, the failure of the visual system to provide expected motion perception in real-time.

Role of the Visual System in Eliciting Motion Sickness

The role of the visual system in eliciting MS has been demonstrated in studies involving the use of an optokinetic drum paradigm for investigating MS (Bubka, Bonato, Urmey, & Mycewicz, 2006; Kennedy, Hettinger, Harm, Ordy, Dunlap, 1996; Stern, Hu, Anderson, Leibowitz, & Koch, 1990). MS is elicited by presenting a rotating visual scene about a stationary subject. The visual system responds to this visual stimulus in the form of an optokinetic nystagmus (OKN).

As previously discussed, the VOR is responsible for making compensatory eye movements to maintain stable retinal images under angular accelerations of the head. This compensatory eye movement is directed from input from the vestibular system.

OKN is another eye movement to achieve gaze stabilization. Unlike the VOR, visual input stimulates OKN. Visual input stemming from the entire visual field, or entire retina, cues the OKN response if any retinal image slip is detected (Draper, 1996). A common experience of this response is when one looks out a car window and sees the world pass by in the opposite direction that the car is travelling. The reason why one doesn't experience a constant blur in vision under this circumstance is due to OKN. The visual scene movement across the entire visual field causes an OKN to occur. An OKN can be characterized by a slow and quick phase of nystagmus (Draper, 1996). First, a slow phase of eye movement occurs. This slow phase is the compensatory eye movement in the same direction as visual scene movement. This eye movement eventually reaches the end of its orbit, resulting in the eye "jumping back" to the start of its orbit. This is accomplished by the quick phase of the OKN.

Participants who are susceptible to MS often experience MS due to the stimulation of this visual stimulus. The OKN creates an illusion of self-motion or vection. Therefore, the visual system mediated by the OKN is providing information that the individual is moving, but since the subject is stationary, the subject's vestibular system is not stimulated, providing information that motion is not taking place. Following Reason and Brand's (1975) sensory-conflict theory of MS, the two systems, vestibular and visual, are providing conflicting sensory information regarding motion: the vestibular system is providing non-motion cues and the visual system is providing motion cues. This often elicits MS symptoms (Bubka et al., 2006; Kennedy et al, 1996; Stern, et al., 1990). This is an example of one role of the visual system in eliciting MS. Generally, following the sensory conflict of MS, the role of the visual system in elicitation of MS is whenever the visual system provides conflicting motion information as compared to other sensory systems.

Vection

Vection is the experience of illusory self-motion when surrounding visual movement, mimicking true motion optical flow, is perceived by a stationary individual (Tschermak, 1931 as cited in Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990; Kennedy, Hettinger, Harm, Ordy, & Dunlap, 1996). Visual movement along any linear or rotational axes of the body can elicit vection (Dichgans & Brandt, 1978, as cited in Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990). One everyday example of this may be experienced when an individual is seated in a parked car and an adjacent parked car pulls out of its parking spot. Vision in the periphery is stimulated by the motion of the car pulling out, which in turn elicits an OKN. As a result, for a moment, the individual in the parked car may sense the uneasy and startling feeling of moving even though the car is still in park.

Sensory conflict theory suggests that concurrent perceived motion by one sensory system and an absence of perceived motion by another sensory system can explain the experience of MS (Reason & Brand, 1975). Therefore, it can be inferred that MS or SS may result when exposed to a vection stimulus while remaining stationary. Hettinger et al. (1990) believed to be the first to confirm this predicted connection. More participants who reported vection while exposed to a flight scenario in a flight simulation VE became sick than those participants who did not report vection (Hettinger et al., 1990).

Specifically, 1 subject out of 5 who did not report vection became sick, whereas 8 participants out of 10 who reported vection became sick (Hettinger et al., 1990).

Although vection has often been suggested to be related to MS, this is not necessarily true. Research examining vection and MS has often found that the condition eliciting the most MS also elicits the most vection (Webb & Griffin, 2003). However, there is lacking evidence to support that there is a causal relation between vection and MS. Similar experiences of MS with and without a strong experience of vection can occur (Webb & Griffin, 2003).

Most studies examining vection and MS are performed with an optokinetic drum (Bubka et al., 2006; Kennedy et al., 1996; Stern et al., 1990). Measurements of vection, MS, and eye movements are gathered while stationary individuals are exposed to a rotating visual scene, usually in the form of vertical stripes. This rotating visual scene elicits an OKN.

It is known that the experience of vection is influenced by peripheral vision, especially in an optokinetic drum (Brandt, Dichgans, & Koenig, 1973; Webb & Griffin, 2003). Following the notion that peripheral stimulation elicits the experience of vection, Webb and Griffin (2003) investigated peripheral and foveal visual stimulation effects on vection and MS.

An HMD was used to present both the foveal and peripheral vision conditions (Webb & Griffin, 2003). The foveal stimulus consisted of a single dot that moved across the center of the display, which immediately “jumped” back to the starting position once it reached the end of the display. Participants were instructed to visually track the moving dot throughout its movement. This condition elicited OKN eye movements. The peripheral stimuli consisted of 5 horizontal rows of dots that moved across the display in the same fashion as the foveal condition with the exception that the dots did not “jump” back to the starting position once reaching the end of the display. Participants in this condition were instructed to “track each dot in the middle row as it passed” (Webb & Griffin, p. 623). It was confirmed by electrooculogram (EOG) data that both conditions elicited similar OKN eye movements.

The findings of Webb and Griffin (2003) suggested that MS, or SS, is not dependent on vection. Vection was significantly greater in the peripheral vision condition than the foveal vision condition, but MS was not significantly different between the two conditions. Also, there was not a correlation between vection and MS within both conditions. However, there was a significant accumulated MS correlation between the two conditions (Webb & Griffin, 2003). Along with this correlation, absence of significant MS difference between the two conditions, and an absence of correlations between vection and MS within both conditions, it was suggested that vection is not a primary cause of MS, or SS (Webb & Griffin, 2003). It was further suggested that MS was elicited by foveal visual stimulation since similar OKN eye movements occurred in both conditions (Webb & Griffin, 2003).

These findings suggested that vection and SS do not vary dependently, and simply reducing peripheral stimulation may not reduce MS (Webb & Griffin, 2002, 2003). Also, the results are consistent with foveal, or central vision being involved in the elicitation of SS, and peripheral vision influencing vection (Webb & Griffin, 2002, 2003).

Stern et al. (1990) demonstrated that a visual field restricted to 15° significantly reduced vection as compared to a full visual field stimulus within an optokinetic drum. When fixating on a centrally located target with full visual field stimulation, vection was also reduced, but not as great as a restricted visual field. MS was significantly reduced, as demonstrated by subjective report and a reduced tachyarrhythmia (gastric rhythm of 4-9 cpm associated with nausea; Stern et al., 1990), with restricted visual field and central target fixation as compared to full visual field stimulation without fixation (Stern et al., 1990). These findings are consistent with previous findings that suggested vection is dominated by peripheral vision (Brandt et al., 1973; Webb & Griffin, 2002, 2003). However, these findings are not congruent with Webb and Griffin (2003) regarding central and peripheral vision influences on MS. Webb and Griffin (2003) did not reveal a difference in MS when peripheral vision was stimulated more than foveal vision, however, Stern et al. (1990) demonstrated a significant reduction in objective and subjective MS symptoms when peripheral vision was reduced through a restricted visual field of 15°.

Changing the degree of conflict between visual and vestibular input within an optokinetic drum has been suggested to significantly affect MS, thus supporting the sensory conflict theory to MS (Bubka et al., 2006). Bubka et al. (2006) utilized a typical optokinetic drum paradigm to examine alternating rotational velocities of a vection stimulus on MS, as measured by the SSQ. Participants participated in rotational velocity conditions of constant 5 rpm, constant 10 rpm, and a condition alternating between 5 and 10 rpm.

Since vestibular input did not exist in any condition, it was thought that the alternating velocity condition would induce a greater sensory conflict between visual and vestibular input, eliciting higher SSQ scores. Post SSQ scores, as expected, were revealed to be significantly higher in the alternating velocity condition as compared to the constant velocity conditions (Bubka et al, 2006). SSQ scores were second highest in the 10 rpm condition, followed by the 5 rpm condition.

However, the visual system is not necessary or sufficient to elicit MS. It is well documented that a functioning vestibular system is necessary for MS to occur (DiZio & Lackner, 2005; Cheung et al., 1991). Further, blind persons can experience MS (Graybiel, 1970). In one study, bilateral labyrinth defective (non-functioning, damaged vestibular system) participants and normal (functioning vestibular system) participants were exposed to rotating optokinetic visual stimulus (random dots; Cheung et al., 1991). It was found that the normal participants experienced MS symptoms 21 out of 27 trials whereas no MS symptoms were reported or observed in the labyrinth defective participants, suggesting that a functioning vestibular system is necessary for the MS to occur (Cheung et al., 1991). Therefore, even though the vestibular system may not be stimulated, it is suggested that a functioning vestibular system is necessary to provide and sense a conflict in sensory information regarding motion.

Types of Virtual Environments

Virtual environments (VEs) are environments in which users can interact in real time with a computer generated three dimensional model of an environment, or interact with objects within the modeled environment (Wilson, 1999). Optimally, users can interact within the VE intuitively and develop a feeling of actually being within the modeled environment. VEs can be displayed to users with different forms of technology such as: HMDs; desktop computers; a simple projection screen on a wall; or a CAVE system (Wilson). A CAVE system is a simulator in which the user is actually situated inside a cubed room and the VE is projected on several screens for up to six surfaces; i.e. four walls, ceiling, and floor (Wilson). Along with these distinctions of how the VE is projected to the user, a further distinction can be made between fixed-base and motion-based simulators. In fixed-base simulators, users remain stationary and do not experience any motion. Conversely, users may experience passive or active motion in motion-base simulators, depending on the VE application. Overall, any modeled or simulated environment depicted to an individual constitutes a VE, whether it may be a video game console, PC-based, or a complex HMD platform. The focus of the current dissertation is on HMD VEs.

Display Parameters and Characteristics of HMD VEs

Simplistically, HMD systems are comprised of a display device attached to the head, a VE, relay optics (mirrors and lenses that project image to display), and a head-tracking system (Velger, 1998, as cited in Patterson, Waterbottom, & Pierce, 2006). HMD VEs have several innate display parameters and characteristics common to all HMDs including: field of view (FOV); update delay; refresh rate; resolution; head tracking; and stereoscopic or monoscopic vision. Other characteristics of HMD VEs, not as readily quantified, are levels of presence and immersion provided by the HMD VE.

The scope of the current dissertation will include FOV, update delay, presence, and immersion.

HMDs are an imperfect technology and as a result, tradeoffs exist with these characteristics. For example, larger FOVs will result in poorer display resolution. Further, the more complex the VE is, coupled with optimal optical and viewing parameters, the greater the update delay. Update delays can result in a negative user experience with an HMD VE. Such consequences of update delay will be discussed in more detail in subsequent sections.

Field of View and Geometric Field of View

Field of view (FOV) is an innate display characteristic of all VE technologies, HMD based or PC based. The effects of FOV manipulation on SS and presence have been investigated in past research. However, research is often ambiguous as to what exactly is being referred to as FOV. It is of some importance to have a better understanding of what FOV may refer to in such research before discussing previous findings.

In VE research, FOV may refer to one of three possible measurements, with each having a different way to reduce or restrict FOV (see Figure 2.2). The one, common, underlying component of all possible FOV measurements is the visual angle subtended from some entity to another. This is where ambiguity arises. Some researchers neglect to adequately operationally define and distinguish what the angle is subtended from and to when mentioning FOV.

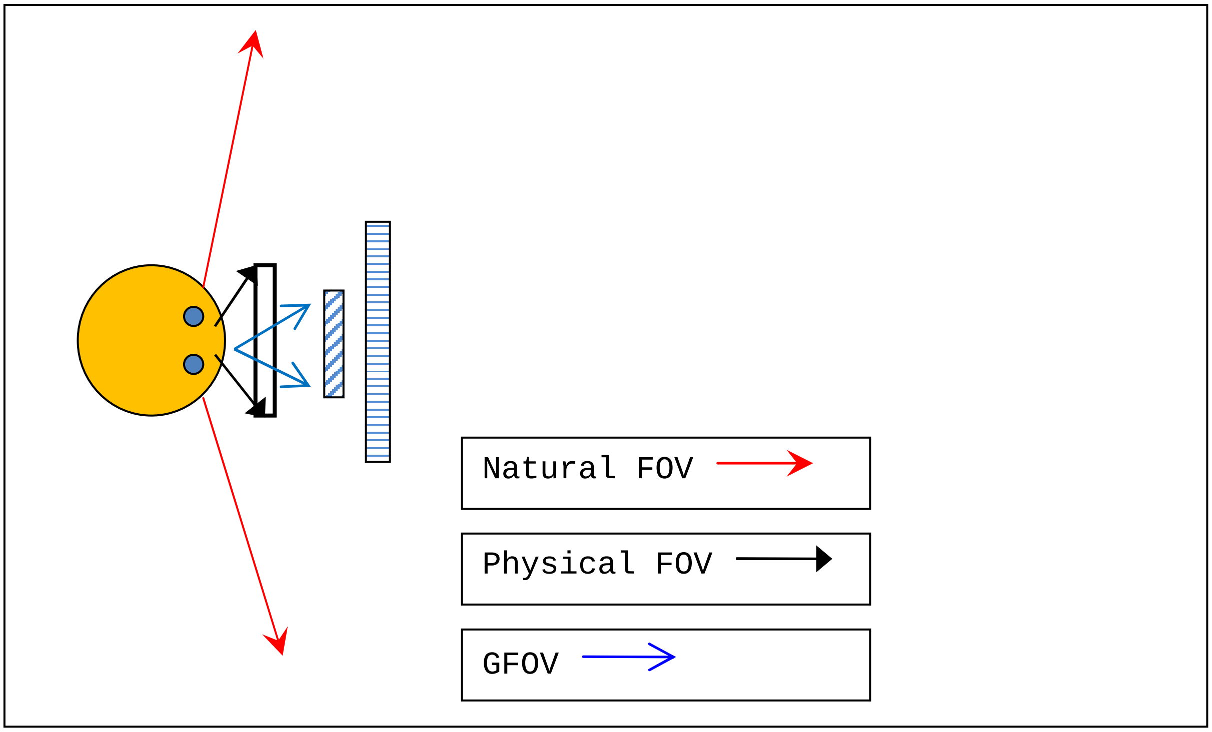

Figure 2.2. Diagram showing three different possible sources of FOV measurements. The circle represents the user. The open rectangle represents the physical display. Diagonal lines depict a GFOV resulting in magnification, or an image scale factor greater than 1. Horizontal lines depict a GFOV resulting in minification, or an image scale factor less than 1.

First, with HMD VEs, FOV may refer to the visual angle subtended from the viewer's position to the horizontal and vertical boundaries of the display of the HMD (Banton, Thompson, & Quinlan, 2001). This FOV is simply the visual angle that an object, or in this case, the display, falls on the retina. This has sometimes been termed physical FOV of the system, and will continue to be referred to as physical FOV herein. See the open rectangle in Figure 2.2. Physical FOV is based on the distance between the user and display, as well as the physical dimensions of the display. Increasing or reducing distance between user and display reduces or increases physical FOV, respectively. Increasing or reducing the size of the display increases or reduces the physical FOV, respectively. The physical FOV is the FOV listed in technical specifications of an HMD.

Second, FOV may refer to the FOV that is depicted, or simulated, in the virtual scene, or VE itself. This FOV is more correctly termed geometric field of view (GFOV). GFOV is the visual angle subtended from the center of projection within the scene to the horizontal and vertical frames of the scene, or viewport (Mourant, Ahmad, Jaeger, & Lin, 2007; Psotka, Lewis, & King, 1998; Hendrix & Barfield, 1996; Banton, et al., 2001). See the patterned rectangles in Figure 2.2. The center of projection often is analogous to the simulated viewer's position in the VE (Draper, 1998). GFOV of VEs is manipulated internally through the software of the VE system. Manipulating GFOV is analogous to zooming in and out with a camera lens. Reducing or increasing the GFOV, or zooming in and out, results in a magnification or minification of the scene, respectively (Farber & Rosinski, 1978; Hendrix & Barfield, 1996). As a result, the amount that an object in the scene occupies on the retina is dependent on GFOV, or with the case of a camera, amount of zoom. Objects occupy more space (increased visual angle) on the retina with reduced GFOVs (magnification) and less space (reduced visual angle) with increased GFOVs (minification). The only case that minification or magnification does not occur is when physical FOV of the display is the same as the GFOV. When the GFOV is greater than the physical FOV, the VE scene is "shrunk" to fit on the display. When the GFOV is less than the physical FOV, the VE scene is "stretched" or magnified to fit the physical FOV. See the patterned rectangles in Figure 2.2.

Regarding possible magnification and minification scene distortion due to varying GFOVs, Hendrix and Barfield (1995) found no perceived compression effects between three GFOVs of 10°, 50°, and 90°. Participants were exposed to a VE that had a physical FOV of 90° with the aforementioned manipulated GFOVs and answered an in-house questionnaire containing one item assessing scene compression.

The consequence of varying GFOVs when physical FOV is held constant has been termed image scale factor (Draper, 1998). The ratio of physical FOV to GFOV is known as image scale factor (Draper, 1998). An image scale factor of unity, or 1, represents a GFOV that is identical to the physical FOV. Whereas, an image scale factor greater than one (i.e. unity) or less than one represents magnification or minification, respectively, of the scene. Therefore, image scale factor more appropriately describes scene magnification and minification distortion than GFOV. However, as abovementioned, research is often unclear as to whether the referenced FOV is physical FOV or GFOV, let alone identifying both metrics. The current researcher is only aware of the work of Draper (1998) and Draper, Viire, Furness, and Gawron (2001) in making the distinction between physical FOV and GFOV in SS research. Image scale factors deviating from unity have resulted in greater SS as compared to an image scale factor of unity, or in other words, when GFOV and physical FOV are congruent (Draper, 1998; Draper, et al., 2001).

Third, FOV may refer to the amount of the user's natural FOV, or visual angle subtended from the retina to the natural environment, that is restricted. Full or unrestricted FOV of human vision is ~180-200° with ~120° of binocular overlap (Lin, Duh, Abi-Rached, Parker, & Furness, 2002; Werner, 1991, as cited in Arthur, 2000). Physical FOV may be restricted by occluding a certain degree of peripheral vision. An example would be the use of blinders or viewing a visual scene through straws. See Figure 2.2 depicting the aforementioned FOVs.

Update Delay

Update delay refers to the temporal difference between head movement in the real world and the processing time of visual scene presentation in the VE. Finch and Howarth (1996) define total system delay as being the "delay in virtual reality systems between inputs by the user and the new scene appearing." In other words, update delay is the time between a head movement and the resulting consequence of that head movement in the VE. This update delay is the sum of all processing and transport times of multiple aspects within the HMD technology (Mania, Adelstein, Ellis & Hill, 2004). Such aspects include the head tracker, tracker driver, simulation application, graphics rendering, and screen refresh rate (Mania et al., 2004). Lag, display lag, total system delay, latency, end-to-end latency are all common terms to describe update delay and are often used interchangeably, but all refer to the above description of update delay.

Past studies have examined update delay discrimination within various VEs (Adelstein, Lee, & Ellis, 2003; Ellis, Mania, Adelstein, & Hill, 2004; Ellis, Young, Adelstein, & Ehrlich, 1999a,b; Mania et al., 2004). Ellis et al. (1999a) first investigated delay discrimination involving hand movements of virtual objects in the task of moving a ball that was virtually attached to their dominant hand. The results suggested that individuals should be able to discriminate delay changes of 33 ms and above (Ellis et al, 1999a). The 50% correct discrimination rate suggested a threshold occurring with ~50 ms in addition to the system delay (27 ± 5 ms) for a threshold of ~77 ± 5 ms.

In a follow-up study, participants performed the task of rocking their head back and forth in an arc subtending 48° (Ellis et al., 1999b). The findings of Ellis et al. (1999b) were essentially identical as Ellis et al. (1999a). Ellis et al. (1999b) suggested a 50% correct discrimination rate, or threshold, to occur with ~33 ms in addition to the system delay (27 ± 5 ms) for a threshold of ~60 ± 5 ms.

Update delay discrimination was further examined as a function of head movement frequencies (Adelstein et al., 2003). Participants viewed a simple VE consisting of a blue octahedral frame and yawed their head ~36° sinusoidally (Adelstein et al., 2003). When results were averaged across all conditions and participants, the just noticeable difference (JND) and the point of subjective equality (PSE), or threshold were 13.6 ms ± 0.6 ms (mean ± standard error) and 58.8 ms ± 2.6 ms, respectively (Adelstein et al., 2003).

Allison, Harris, Jenkin, Jasiobedzka and Zacher (2001) investigated the effects of update delay and velocity of head movements on the threshold of the onset of oscillopsia. This is the perception of an unstable environment that appears to “swim about or oscillate in space” within a VE (Allison et al., 2001). It was suggested that thresholds for head velocities of 22.5°/s, 45°/s, and 90°/s were ~200 ms, ~110 ms, and ~60 ms in addition to the total system delay (122 ms), respectively (Allison et al., 2001).

The discrepancy between the thresholds suggested by Allison et al. (2001) and Ellis et al. (1999a,b), as well as Adelstein et al. (2003) led to the examination of delay detection in different VEs to investigate the generality of previous delay discrimination studies (Ellis et al., 2004). Based on the discrepancies between threshold results and virtual scenes, Ellis et al. (2004) examined delay detection using one of three environments. One condition replicated the environment used by Allison et al. (2001), another replicated previous studies (Adelstein et al., 2003; Ellis et al., 1999a,b) and the third combined the features of the former scenes. Thresholds and JNDs ranged from ~26-32 ms and ~10-14 ms, respectively across all conditions. Hence, the discrepancies between delay detection research as suggested by Ellis et al. (2004) and Allison et al. (2001) have not yet been explained.

The generality of update delay sensitivity in VEs was further investigated using a realistic HMD VE (Mania et al., 2004). The realistic virtual scene examined was a rendering of two interconnected rooms that included real world objects. The JND and threshold suggested by Mania et al. (2004) with a realistic virtual scene were 9.1 ms ± 1.6 ms and 14.3 ms ± 2.7 ms, respectively.

Previous research in our laboratory examined perceptual thresholds for delay detections utilizing a “real” visual scene (Moss, Muth, Tyrrell, & Stephens 2005). Participants reported if delay was present or absent in the visual scene and a threshold was obtained by a binary search method. A mean threshold (± standard deviation) of 193 ms (± 121 ms), median of 180 ms, mode of 40 ms, and a lower and upper quartile range of 85 to 300 ms was revealed.

This high within variability for delay threshold along with the discrepancies in reported thresholds ranging from 14 ms (Mania et al., 2004) to 322 ms (Allison et al.,

2001) suggests the ability for users to detect and notice delays is not held constant. Also, the variability between and across multiple studies may indicate update delay is not the sole source of a vestibular and visual conflict causing SS.

Presence and Immersion

It is widely accepted that a key component to the utility of an HMD is the amount of presence the HMD VE affords (Jerome, Darnell, Oakley, & Pepe, 2005; Witmer, Jerome, & Singer, 2005; Witmer & Singer, 1998). Presence has been described as the subjective feeling of being in a different environment than the current physical locale the user is in while participating in an HMD application (Witmer & Singer, 1998). Presence was further defined as "a psychological state of 'being there' mediated by an environment that engages our sense, captures our attention, and fosters our active involvement, (Witmer et al., 2005, p. 205)." In other words, it is how much the user believes he is actually "in" the VE that the HMD depicts. An example of this would be a Naval aviator undergoing a training mission in a flight simulator over the Iraq desert while on board of an aircraft carrier. In theory, if the aviator experiences a maximal sense of presence while in the simulator, he or she will feel as if located over the Iraq desert and no longer on board the aircraft carrier in the real, external world.

Witmer and Singer (1998) discuss the concepts and necessary components to achieve the psychological construct of presence. Directed attention and the interaction between immersion, involvement, and individual tendencies to become involved are required to achieve presence (Witmer and Singer, 1998). Immersion is a characteristic of HMDs important to the sense of presence. Therefore, it is important to distinguish between immersion and presence. While immersion and presence are often used to refer to the same experience, they are not analogous, but immersion is necessary to achieve optimal presence.

“Immersion is a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences (Witmer and Singer, 1998, p. 227).” Slater, Linakis, Usoh, and Kooper (1996) objectively describe immersion as a quantifiable description of the technology of the VE platform in terms of how isolated the user is from external, real world stimuli. Increasing this isolation increases the degree of immersion (Witmer and Singer, 1998). Simply stated, in less immersive VEs, users feel as if they are on the “outside” of the VE looking in, and conversely, in more immersive VEs, users feel as if they are on the “inside” of the VE (Witmer and Singer, 1998).

HMD VEs and PC based VEs are examples of VEs that differ on levels of immersion. HMDs, especially those that provide auditory stimuli, isolate users from the external real world more than a PC based VE. Slater et al. (1996) would describe the PC based VE as a low immersive VE and an HMD VE as a high immersive VE. Theoretically, in a maximal immersive HMD VE, all sensory input the user would receive would be provided by the HMD VE. All real world visual stimuli would be completely isolated from the user as well as all real world auditory stimuli. The HMD VE would provide all sensations. Peripheral vision would be completely occluded as well as all background sound or noise from the real world environment. In a PC desktop

VE, the user is seated in front of the monitor. The real world environment is not isolated from the user. The user is free to look around the real world if he chooses to. Even when solely attending to the VE depicted by the monitor, peripheral visual stimuli in the real world are still present and being processed by the user. The user could be disrupted by many possible occurrences in the real world. In a high immersive HMD VE, in theory, the user would be oblivious to his or her real world physical surroundings and only have knowledge of the occurrences taking place in the VE.

It is more likely to experience the subjective sense of presence in a high immersive VE, such as an HMD VE, than a low immersive VE (Witmer & Singer, 1998; Slater et al., 1996). However, one may experience presence in a low immersive VE. The user may be extremely engaged in the VE application and devote a high amount of attention to the application and in turn, experience a sense of presence.

Even though isolation from real world stimuli is accomplished mostly by technological aspects and equipment configuration of the VE technology, Witmer and Singer (1998) disagree with the view of immersion being solely an objective description of the VE technology (Slater et al., 1996). Immersion is experienced by the user, just as is presence (Witmer and Singer, 1998). Immersion is experienced by the user not only through technological aspects, but also through how well the VE affords users to interact naturally within the VE as part of the continuous stream of stimuli (Witmer and Singer, 1998).

Being involved in the VE is necessary to achieve presence. Involvement depends on the meaningfulness the user places on the VE activity as well as how much attention is focused on the VE (Witmer and Singer, 1998). Playing a video game that a user is highly fond of may be very meaningful to a user and will probably capture most of the user's focused attention. However, according to Slater et al. (1996), it is not highly immersive. The user is still in the real world room looking in at the VE depicted on the display.

Based on the theoretical concept of immersion provided by Slater et al. (1996), physical equipment of the VE platform can alter the amount of immersion. An example of this can be seen with some HMDs. When donning an HMD, the display is located in front of your eyes. However, some HMDs do not provide peripheral occlusion from the external environment. In other words, there may not be any physical enclosure between the eyes and the display of the HMD permitting both peripheral vision of the external environment and central vision of the VE. It can be argued, solely based on Slater et al. (1996), that an HMD providing a surrounding enclosure would provide for a more immersive VE, whereas the converse would be less immersive. Therefore, in the current study, this physical aspect of the HMD VE will be manipulated. The HMD used in the current study offers the ability to manipulate occlusion of peripheral vision from the external environment. "Eye-cups" may be physically attached to the display of the HMD that when the HMD is donned, extend from the display and surround each eye, occluding visual stimuli from the external environment.

Problems with Virtual Environments

HMD VEs are becoming a more common training tool in simulating real world applications. However, HMD VEs are imperfect in simulating the real world. These imperfections have been documented to result in adverse effects. Adverse effects include improper or inadequate transfer of training from the VE to the real world application and simulator sickness (SS) (DiZio & Lackner, 1997; Finch & Howarth, 1996; Wilson, 1996; Regan & Price, 1994; Kennedy, et al., 1989).

Flight simulators are often used in training. However, SS may arise. Kennedy et al. (1989) surveyed and reported incidents of SS among pilots (N=1186) from 10 of the U.S. Navy's flight simulators (none of which were HMD based). Incidents of sickness were reported as high as 60% among the pilots (Kennedy et al., 1989).

Simulator sickness may cause problems in regards to safety and health, training, and operational readiness (Kennedy et al., 1989). Possible hazards to safety and health include visual after-effects (Kellogg, Castore, & Coward, 1980; as cited in Kennedy et al., 1989), and locomotor ataxia, which are detrimental postural changes (Crosby & Kennedy, 1982; as cited in Kennedy et al., 1989). These hazards to safety and health may limit training effectiveness as distrust and trepidation towards the simulators may precipitate among the users (Kennedy et al., 1989).

The occurrence of SS may also lead to less than optimal transfer of training from the simulator to the real world application. An individual, in this case a pilot may recognize susceptibility to SS, and thus attempt to limit or avoid SS. The individual may accomplish this by adopting perceptual-motor strategies in order to avoid the onset of sickness (Kennedy et al., 1989). SS may be reduced, or even avoided, but these adopted strategies may be inappropriate in the real world setting, thus producing poor and/or negative transfer of training to the real world (Kennedy et al. 1989).

Operational readiness of trained individuals may also be sacrificed due to the experience of SS. The ability to perform post-simulator activities may be restricted due to the necessity of allowing the individual to overcome severe symptoms of sickness and disorientation (Kennedy et al., 1989). Not allowing the individual to overcome these symptoms may put the individual or others at risk while performing the real world application.

Update Delay and Field of View Effects on Simulator Sickness and Presence

Update Delay and Simulator Sickness

The affects of field of view (FOV) and update delay on SS severity when immersed in a HMD VE have been previously investigated by DiZio and Lackner (1997). The results suggested that SS severity increased in a monotonic fashion as update delay increased (DiZio & Lackner, 1997). Interestingly, even minimal update delay (67 ms inherent of the HMD) induced significant SS (DiZio & Lackner, 1997). Also, two participants withdrew during the 67 ms delay condition due to SS, as well as six others during the maximum delay condition (367 ms). SS severity was reduced in half in the reduced FOV with 200 ms delay condition (63° X 37° vs. 126° X 74°). Manipulating weight of the HMD did not have an effect on SS (DiZio & Lackner, 1997).

DiZio and Lackner's (1997) results demonstrated the relationship of update delay (inherent and additional) and SS in HMD VEs. Their findings also provide an empirical basis for examining the effect of varying FOVs on SS. It can be inferred that the possible benefits of a full FOV, in regards to levels of user immersion in a VE, do not outweigh the costs if users develop SS and are not able to fully complete a VE session.

Furthermore, if it is not possible to reduce update delay in a VE system, minimally, the FOV could be reduced to minimize SS.

Update delays of and greater than 184 ms have been reported to steadily induce SS symptoms in helicopter flight simulation (Jennings, Reid, Craig, & Kruk, 2004). Three helicopter pilots participated in a typical flight simulator task in which visual update delays of 67 ms, 134 ms, 184 ms, and 334 ms, as well as control delays of 85 ms, 162 ms, 212 ms, and 362 ms were investigated on SS symptoms and handling. Pilots used an HMD in the flight simulator as is used in helicopter flight. Update delays affected handling performance as expected. SS symptoms tended to increase as visual update delay increased, but consistent SS symptoms were not reported until relatively longer delays of 184 ms and greater. SS symptoms were reported more frequently for visual delays than control delays.

Similar to Jennings et al. (2004), Wildzunas, Barron and Wiley (1996) revealed that severe SS was not reported until relatively long delays were present. Additional delays of 0, 67, 133, 267, 400, and 533 ms to the inherent delay of 116 ms were investigated on pilot performance and SS in a flight simulator (Wildzunas et al., 1996). Significant main effects of delay were revealed on SS (Wildzunas et al., 1996). SS increased as delay increased, with a marked increase between 400 ms and 533 ms of delay. The update delay of 533 ms elicited significantly greater SS than all other delays (Wildzunas et al., 1996). Also, a significant interaction was reported between delay condition and trial. SS was significantly greater after trials 2 and 3 of each delay condition as compared to the first trial of the day (Wildzunas et al., 1996). Performance was not significantly degraded until 400 ms of delay. These findings once again suggest SS is not a simple function of update delay. Although SS was greater with longer delays, SS increased after additional exposures (trials) even in the smallest delay conditions.

Nelson, Roe, Bolia, and Morley (2000) investigated the effects of update delay, time on task, and task complexity on subjective ratings of SS in a “see-through” HMD. SS was not revealed to be significantly affected by update delay. Participants took part in a within-subjects design consisting of three update delay conditions and two task conditions (Nelson et al., 2000). Update delays were the inherent delay of the HMD (46 ms), inherent plus 50 ms, and inherent plus 100 ms. In the tracking task, participants simply had to track a moving visual target. The visual monitoring task required the subject to inspect the display and respond when critical signals were detected. Nelson et al. found a significant main effect for time of task (experimental trials), and a significant task X time of task interaction. It is important to note that time of task X delay interaction approached significance. A significant effect of update delay was not revealed. These findings demonstrated that Simulator Sickness Questionnaire scores (SSQ; Kennedy, Lane, Berbaum, & Lilienthal, 1993) increased in the single task condition as time increased.

Although Nelson et al. (2000) demonstrated that update delay did not significantly affect SS; these findings are important to the present study. It was demonstrated that greater SS existed with minimal delays that are inherent in HMDs, as suggested by the inherent delay condition having the highest SSQ score than the other delay conditions.

Overall, these findings suggest that time of task was the leading contributor to SS and SS is not simply a function of update delay.

Draper et al. (2001) further suggested that SS was not a function of update delay. Update delay was varied with levels of 125 ms and 250 ms, while image scale factor was held constant at unity, or in other words, when GFOV was congruent with physical FOV. Participants performed a visual search task in an HMD VE. Image scale factor as a consequence of varying GFOVs was also examined on SS in a separate experiment (Draper et al., 2001). This aspect of the experiment will be discussed in a subsequent section. Simple exposure to the HMD VE exposure elicited significant SS when conditions were collapsed (Draper et al., 2001). Post SSQ scores were higher than pre SSQ scores. Pertinent to the present study, a significant effect of delay on SS was not revealed. Interestingly, as indicated by Figure 8 in Draper et al. (2001), mean and median SSQ scores were higher in the 125 ms condition.

The results of Draper et al. (2001) are conflicting to previous research suggesting an increase in SS as delays increase (DiZio & Lackner, 1997, Jennings et al., 2004; Wildzunas et al., 1996). SS appeared to be greater in the 125 ms condition as compared to 250 ms. It is also interesting to note that SS was not revealed to be a function of delay, even when eight out of the 10 participants reported past experienced MS. It is possible to infer that if delay was a factor on SS, the effects would be more pronounced since eight of 10 participants reported experiencing MS in the past, suggesting more susceptibility to SS, but this was not the case.

Comparable to Draper et al. (2001), a delay of 280 ms failed to show a significant effect on MS while performing an HMD task in So (1994). Participants in So donned an HMD and viewed a simulated aircraft flight. Participants had the perspective of being in one aircraft following another aircraft in flight. The participants' task was simply to keep the view of the aircraft in the center of their FOV by moving their head appropriately. This task was performed in delay conditions of 280 ms and an inherent delay condition of ~75 ms (no additional delay). This task was also performed in a condition with no additional delay and with a target offset to examine head movements. SS measurements were obtained as well as a measure of perceived realism. The 280 ms delay condition did not significantly affect SS, nor did head movements (So, 1994). However, a significant positive correlation between SS and realism was revealed (So, 1994).

The results of So (1994) and Draper et al. (2001) suggest the further exploration of HMD characteristics other than delay in the development of SS. As suggested by So (1994), perceived realism of the HMD VE warrants further investigation in its relationship with SS, and will be examined in the current study, in the form of Witmer and Singer's (1998) presence construct.

Moss, Williams, and Muth (2008) further suggested the lack of a strong influence of delay on SS. A within-subject design was used to investigate the effects of no additional delay and ~200 ms of additional delay on a simple search task donning an HMD. The HMD depicted a real world scene of our lab through a mounted video camera on the HMD. Each participant performed a series of 5, 2 min search task trials by locating embedded objects in the lab that were called out by a pre-recorded audio tape.

Like Draper et al. (2001), a significant main effect was revealed for trial, or exposure time performing the task. SS, as obtained by the SSQ, increased in both delay conditions as trials, or exposure time increased. Even though 2 participants failed to complete the entire 200 ms delay experimental session, only a marginally significant increase in mean peak SSQ scores between no additional delay (M=33.83, SE=6.65) and ~200 ms of additional delay (M=43.57, SE=7.53; t=-1.708, p=.051) was revealed by a one-tailed paired-samples t-test.

In summary, there is inconsistency in previous research regarding update delay effects on SS. It seems that previous research can be somewhat evenly divided among research that has revealed strong update delay effects on SS (DiZio & Lackner, 1997; Jennings et al., 2004; Wildzunas et al., 1996) and research that hasn't revealed any update delay effects on SS (Draper et al., 2001; Nelson et al., 2000; So, 1994). Moss et al. (2008) revealed only a marginally significant update delay effect on SS.

Research that has revealed significant effects on SS have utilized update delays ranging from no additional delay up to 533 ms of additional delay (DiZio & Lackner, 1997; Jennings et al., 2004; Wildzunas et al., 1996). Update delays ranging from no additional delay up to 280 ms of additional delay have been used in research that has not suggested any significant effects on SS (Draper et al., 2001; Nelson et al., 2000; So, 1994).

However, Nelson et al. (2000) and Draper et al. (2001) suggested greater SS in their lower update delay conditions of 46 ms and 125 ms, respectively, as compared to their higher update delay conditions of 100 ms and 250 ms, respectively. Conversely, Jennings et al. (2004) and Wildzunas et al. (1996), which have revealed significant update delay effects on SS, have suggested a marked increase in SS in higher update delay conditions of 184 ms and 533 ms, respectively, as compared to their lower conditions. This observation may provide evidence for a possible existence of a curvilinear relationship between update delay and SS. In other words, SS may increase and decrease around some critical level of update delay. SS may be greater with lower update delays and then decrease as update delays increase up to some critical level of delay, possibly somewhere around 200 ms, and then SS increases as update delays continue to increase.

DiZio and Lackner (1997) would dispute such a relationship since they revealed SS to increase as a function of update delay in a consistent fashion. Therefore, based on limited research and DiZio and Lackner (1997), it would be premature to suggest a distinct curvilinear relationship between update delay and SS. Although it is not the purpose or scope of the current study to explore such a relationship, this possible relationship does warrant further examination. Overall, the effect of update delay on SS is not straightforward as demonstrated by the previously described incongruent research. Further research would be beneficial.

Update Delay and Presence

Update delays have also been examined regarding sense of presence in VEs (Barfield & Hendrix, 1995; Meehan, Razzaque, Whitton, & Brooks, 2005). Update rates of 5, 10, 15, 20, and 25 Hz, or update delays of 200, 100, 66.7, 50, and 40 ms, respectively, were investigated by Barfield and Hendrix (1995). Participants navigated a virtual rendering of Stonehenge and searched for inscriptions. Each subject was exposed to each update delay condition. An in-house presence questionnaire was used to assess presence, which was used in previous work by the researchers (Hendrix & Barfield, 1995).

Presence was revealed to be significantly less in the 200 ms condition than the other conditions, with the exception of the second longest delay of 100 ms (Barfield & Hendrix, 1995). Moreover, Barfield and Hendrix (1995) suggested no additional increase in presence with delays lower than 66.7 ms. Presence was not significantly different between 200 ms and 100 ms, 100 ms and 66.7 ms, or between 66.7 ms, 50 ms, and 40 ms (Barfield & Hendrix, 1995). Overall, it was suggested that delays do not have to be lower than 66.7 ms to achieve presence in a simple search task within a VE (Barfield & Hendrix, 1995). Similar results were also obtained from a later, related study (Barfield, Baird, & Bjorneseth, 1998). The implication of this research (Barfield et al., 1998; Barfield & Hendrix, 1995) on the current study suggested presence should be different between delay conditions less than and greater than 66.7 ms.

Subjective, self-report measures obtained from questionnaires are often used to assess participants' sense of presence within VEs. Researchers have also attempted to measure presence using physiological measures concurrently with questionnaires (Meehan et al., 2005). Meehan et al. (2005) measured the effect of update delay on heart-rate while participants participated in either, what the researchers termed, a stressful VE or a less stressful VE. Update delays of ~50 ms and ~90 ms were examined in both VEs. The stressful VE depicted a room in which the participants' point of view was 20 feet above while standing on and looking over a small ledge. The less stressful VE depicted participants' point of view from the floor of the room. It was thought that a greater physiological response, in the form of change in heart rate, would exist in the more stressful VE condition with low update delay (~50 ms; Meehan et al., 2005).

Meehan et al. (2005) hypothesized a change in heart rate in the stressful VE with lower update delay would demonstrate a greater belief of being in the stressful VE, or greater presence. The higher update delay of ~90 ms was thought to diminish the belief that the participants were in the stressful VE, and manifest as lower heart rates.

The results, regarding physiological response, supported a greater change in heart rate for the more stressful VE with lower update delay than higher update delay (Meehan et al., 2005). Change in heart rate was higher in the stressful VE than the less stressful VE, confirming a reliable physiological response to stress. Change in heart rate was 3.1 beats per min larger with a delay of ~50 ms than ~90 ms when in the stressful VE. This difference was marginally significant (Meehan et al., 2005). Therefore, it can be inferred that an update delay of ~90 ms did diminish participants' belief of being in the VE, as seen solely by physiological response. However, a significant difference in a self-report of presence was not revealed between the two delay conditions (Meehan et al., 2005). The direction of the self-reported measure was congruent to the physiological response. Albeit non-significant, self-reported presence was higher in the ~50 ms condition (Meehan et al., 2005).

Meehan et al. (2005) demonstrate another possibility of measuring presence within a VE, which should warrant further development in this technique. Based on

Meehan et al. (2005), greater presence should be expected with lower delays. It is necessary to note, however, that participants were gathered at a conference during a demonstration. Such factors, amongst others, of alcohol consumption, recent exposure to other VEs, general stress, and lack of sleep were not controlled (Meehan et al., 2005).

Presence was also measured in the previously discussed research of Moss et al. (to appear 2008). Significantly higher presence scores were reported in the condition of minimal update delay (M=151.1, SE=6.36) as compared to the condition of ~200 ms (M=139.8, SE=5.85) t=4.093, p=.001. The current study's design will be similar to this previous work and will include identical update delay conditions. Therefore, the results support a hypothesized increase in presence in the current study's minimal delay condition.

Field of View and Simulator Sickness

Prior to the discussion of how FOV affects user's experience in an HMD VE, it is important to note how restricted FOVs affect typical activities in the natural, real-world environment. Alfano and Michel (1990) demonstrated the basic detrimental effects of restricted FOVs while performing regular activities in the real-world, as well as the effect of restricted FOV has on general bodily discomfort as compared to performing those activities with unrestricted FOV.

Alfano and Michel (1990) examined restricted FOVs of 9°, 14°, 22°, and 60° on performance of visuomotor tasks of walking, reaching, and forming a cognitive map of a room. Normal FOV was restricted by wearing goggles that afforded the previous mentioned FOVs.

Alfano and Michel (1990) revealed that restricted FOV diminished perceptual and visuomotor tasks. Across all restricted FOV conditions, participants took more time, formed more misperceptions, and made more errors with all tasks as compared to participants with full, unrestricted FOV (Alfano & Michel, 1990). Performance decrements were most severe with a FOV of 9° and least severe with a FOV of 60°. Also, participants with restricted FOVs reported more discomfort, whereas participants with full FOV did not report any feelings of discomfort.

HMD display parameters or characteristics have been the subject of examination regarding experiences with HMD VEs. GFOV and FOV are two such parameters. To state, physical FOV refers to the visual angle subtending from the user's viewpoint to the physical dimensions of the HMD display itself. GFOV is the visual angle encompassed in the VE scene itself. The majority of previous research has suggested that the experience of SS is more prevalent with wider FOVs (DiZio & Lackner, 1997; Lin, Duh, Abi-Rached, Parker, & Furness, 2002; Seay, Krum, Hodges, & Ribarsky, 2001).

The effects of FOV on SS have also been examined in use of a driving simulator VE (Lin et al., 2002; Seay et al., 2001). Seay et al. (2001) investigated physical FOVs of 60° and 180° on SS. Participants completed the SSQ before and after performing a 10 minute driving simulator task. Although, no significant main effect of FOV was found for total SSQ scores, there was a significant main effect of FOV on the nausea subscale of the SSQ (Seay et al., 2001). Participants experienced more nausea in the 180° condition than the 60° condition.

More levels of FOV were examined to investigate if SS increased in a linear fashion as a function of FOV (Lin et al., 2002). Four FOVs (60°, 100°, 140°, and 180°) were manipulated to examine the effects on SS while being exposed to a driving simulator VE. Participants were exposed to all FOV conditions over a series of passive "drive-throughs" lasting 1 – 1.5 hr in the VE of *Crayolaland* (Lin et al., 2002). Although a significant main effect of FOV on SS was suggested, SS did not increase in a linear fashion as FOV increased (Lin et al., 2002). SS was greatest in the widest FOV (180°) condition, but SSQ scores approached asymptotes beyond 140° (Lin et al., 2002). Post hoc pairwise comparisons of SSQ scores revealed significant differences between all FOV pairs, except between 60° and 100°, and between 140° and 180°. The results of Lin et al. (2002), which revealed the effect of FOV on SS was less pronounced as FOV approached beyond 140°, may suggest the existence of a critical point regarding the affect of FOV.

Draper et al. (2001) investigated the common simulation imperfections of GFOV in HMD VE interfaces on SS. More specifically, image scale factor was examined. The nature of sensory mismatch between the vestibular and visual system involving varying image scale factors of HMD VEs is one of optic flow rate (Draper et al., 2001). Optic flow rate fluctuates with image scale factor, whereas vestibular stimulation remains constant (Draper et al., 2001). An image scale factor causing scene magnification will result in an increase in optic flow velocity as compared to an image scale factor of unity, or less than unity (Draper, 1998; Draper et al., 2001). It was hypothesized that SS would be greater when image scale factor was not of unity, or when minification or magnification of the VE occurred. The conditions were magnification (image scale factor of 2 with GFOV of 12°), neutral (image scale factor of 1 with GFOV of 25°), and minification (image scale factor of .5 with GFOV of 50°).

As hypothesized, significant SS occurred when image scale factor deviated from unity (Draper et al., 2001). SS was significantly lower with an image scale factor of 1 as compared to both image scale factors of .5 and 2. SS was higher with an image scale factor of .5 as compared to an image scale factor of 2, however a statistically significant difference was not suggested (Draper et al., 2001). Measures of angular yaw acceleration were also collected. Acceleration was significantly less with an image scale factor of 2 as compared to an image scale factor of .5 (Draper et al., 2001). However, the differences in angular yaw accelerations were not found to have any effect on SS (Draper et al., 2001). Draper et al. (2001) inferred that reduction in acceleration was a result of increased optic flow in the magnification condition, i.e. image scale factor of 2. Draper (1998) obtained similar results. SS was significantly greater when image scale factor deviated from unity. Although not statistically significant, SS was greater with an image scale factor of .5 than an image scale factor of 2.

The results of Lin et al. (2002) and Seay et al. (2001) provided support for the hypothesis that a wider FOV will elicit more SS. In addition and even though not statistically significant, SS was greater with the widest GFOV as compared to the narrowest GFOV in Draper (1998) and Draper et al. (2001).

Contrary to the previously mentioned research (DiZio & Lackner, 1997; Lin et al., 2002; Seay et al., 2001), no significant effects of FOV on SS were revealed in an unpublished dissertation (Arthur, 2000). Arthur examined physical FOV on general spatial and locomotion performance tasks in an HMD VE. Pertinent to the present study, SSQ scores were also investigated. Prior to Arthur's study, most research involved HMDs with smaller physical FOVs of about 40°-60° horizontally by 30°-45° vertically. The HMD used by Arthur had the largest nominal physical FOV available on the market at the time of 176° wide.

Significant effects of physical FOV on SS were not revealed (Arthur, 2000). However, non-statistically significant trends were suggested. Interestingly and in opposition of what was hypothesized, the trend for mean total SSQ scores was revealed to decrease as physical FOV increased. The only significant difference revealed on SSQ scores was exposure time for each day. SS increased as exposures increased. SS was significantly greater after exposure two as compared to exposure one, but not after exposure three as compared to exposure two. SS increased as more experimental trials were completed. Significant effects of physical FOV were found on performance tasks. Performance on walking and searching tasks with physical FOVs of 48° and 112° were significantly degraded as compared to 176° (Arthur). Arthur suggested a possible lack of power due to the small sample size for not finding any significant effects of physical FOV on SS or presence. However, power was high enough to find effects on performance.

Arthur's (2000) results suggested that the relationship between physical FOV and SS may not be as straightforward as many hypothesize. FOV may play a role in eliciting SS, but clearly it is not the sole predictor of SS experienced as suggested by the lack of effect and trend opposite to the predicted direction. As long as there are contradictory findings in the research, further examination is warranted.

Previous pilot work in the Human Stress and Motion Science Laboratory in the Psychology Department at Clemson University briefly examined image scale factor effects on SS when performing head movements donning an HMD. Unlike other research that has examined SS with use of an HMD VE, pilot work in the laboratory used a real-world scene displayed to participants via an HMD. Participants donned an HMD which had a video camera mounted on top of the camera to provide the real-world scene. The video captured by the camera was projected to the participant through the HMD. Image scale factors were manipulated by using 4 lenses that provided GFOVs of ~30°, ~38°, ~49°, and ~64°. The physical FOV of the HMD was 40°, which provided image scale factors of 1.33, 1.05, .82, and .63, in respect to the abovementioned GFOVs. Choices of GFOV, and consequential image scale factors, were limited to what lenses were available in the laboratory. Image scale factor did not have a significant effect on total peak SSQ scores; however, a trend of increasing peak SSQ scores as image scale factor decreased was suggested. It is important to note that this pilot work did not have much power. It was a between-subjects design consisting of only 16 participants.

Field of View and Presence

Physical FOVs also have been investigated on presence (Seay et al., 2001). Seay et al. (2001) investigated physical FOVs of 60° and 180° on presence. Participants completed the Presence Questionnaire (PQ; Witmer & Singer, 1998) after the completion of a 10 minute driving simulator task. Presence was suggested to be significantly greater in the 180° condition (Seay et al., 2001). Seay et al. (2001) suggested that the conspicuity of the two blank projection screens of the simulator in the 60° condition served as a constant reminder that the participants were indeed in a VE, and as a result, experienced less presence. The results of Seay et al. (2001) provided support for the hypothesis that a wider FOV will elicit more presence. Even though SS was also greater with the wider FOV, as discussed in a preceding section, there was no significant correlation found between SS and presence. The relationship between SS and presence is still unclear and this warranted further examination of the relationship between SS and presence in the current study.

Similar to Seay et al. (2001), Lin et al. (2002) revealed presence to be greater in wider FOVs. Four FOVs (60°, 100°, 140°, and 180°) were manipulated to examine the effects on an in-house presence questionnaire while being exposed to a driving simulator VE. Even though presence was greatest in the widest FOV condition (180°), presence did not increase in a linear fashion as FOV increased (Lin et al., 2002). Similar to SSQ scores (discussed above), presence scores approached asymptotes beyond 140° (Lin et al., 2002). Post hoc pairwise comparisons revealed significantly less presence scores with

60° as compared to 100°, 140°, and 180°. Additionally, presence was significantly less with 100° as compared to 180° (Lin et al., 2002).

Most interesting, and unlike Seay et al. (2001), a significant positive correlation was revealed between SS and presence (Lin et al., 2002). It must be noted that the assessment of presence was different between Seay et al. (2001) and Lin et al. (2002). It is often hypothesized that the experience of SS will diminish the sense of presence (Witmer & Singer, 1998), therefore suggesting a negative correlation. It is thought by Witmer and Singer (1998) that the experience of SS will lead users to withdraw attention from the VE and inwards towards self-awareness of SS, reducing users involvement and engagement, and therefore, resulting in the diminished sense of presence. Once again, this provided another example of uncertainty between the relationship of presence and SS, warranting further examination of the possible relationship.

Hendrix and Barfield (1996) examined GFOVs of 10°, 50°, and 90° on presence while exploring a VE in a within-subjects study. The physical FOV of the projection screen was 90°, which permitted one condition to have a one to one mapping between GFOV and physical FOV, or an image scale factor of 1. Presence was hypothesized to be greatest in the 90° GFOV condition since it represented an image scale factor of unity and therefore, no display distortion of minification or magnification took place (Hendrix & Barfield, 1996).

Presence was suggested to be significantly greater with 50° (image scale factor of 1.8) as compared to 10° (image scale factor of 9), and 90° (image scale factor of 1) as compared to 10°. A significant difference was not revealed between 50° and 90°

(Hendrix & Barfield, 1996). The finding that presence was not significantly different between image scale factors of 1.8 and 1 suggested that an image scale factor between 1.8 and 1 may be necessary to elicit presence, and once again, presence does not increase in a linear fashion as a function of FOV, similar to the findings of Lin et al. (2002). It also can be inferred that any existing magnification distortions between a GFOV of 50° and a physical FOV of 90°, or an image scale factor of 1.8, did not affect presence. For purposes of the current study, Lin et al. (2002), Seay et al. (2001), and Hendrix and Barfield (1996) provided support for the hypothesis that presence may be greatest with a wider FOV.

A small pilot study conducted in the Human Stress and Motion Science Laboratory in the Psychology Department at Clemson University examined image scale factors of 1.33, 1.05, .82, and .63 on presence by manipulating GFOVs of ~30°, ~38°, ~49°, and ~64°, respectively. The physical FOV of the HMD was 40°. Participants performed head movements donning an HMD. The HMD provided a real-world scene of the laboratory. Image scale factor had a significant effect on presence, but in a surprising direction. Contrary to previous research that has suggested an increase in presence as FOV became wider (Lin et al., 2002; Seay et al., 2001), presence was least in the GFOV of ~64° (image scale factor of .63) condition and greatest in the ~38° (image scale factor of 1.05) condition. It is interesting to note that the GFOV of ~38° is closest to an image scale factor of unity. Therefore, greater presence may not be associated with wider physical FOVs or GFOVs, but rather GFOVs that provide image scale factors near unity. However, Hendrix and Barfield (1996) did not reveal significantly greater presence with an image scale factor of 1 as compared to an image scale factor of 1.8. A significant negative correlation was also suggested between PQ scores and SSQ scores (discussed above). As suggested by Witmer and Singer (1998), attention may have been directed inward rather than to the scene as one experienced more SS, diminishing sense of presence.

It has been hypothesized that individuals in a VE construct subjective rest frames (Prothero, Hoffman, Furness, Parker, & Wells, 1995). Prothero et al. (1995) state that a rest frame is a perception of space that an individual perceives to be stationary, therefore all external movement is relative to this adopted rest frame. The experience of presence may be influenced by what the individual adopts to be a reference point as stationary, or rest-frame. Prothero et al. (1995) initially investigated their "rest-frame" hypothesis by manipulating where FOV was physically manipulated while individuals were in an HMD VE. The physical FOV of the HMD was 105°. FOV was restricted to 60°, either by "foreground occlusion" or "background occlusion" (Prothero et al., 1995).

It is not in the scope or purpose of the current study to discuss the hypothesized notion of "rest-frames," but the results of Prothero et al. (1995) are pertinent to restricted FOV effects on presence and potentially to the design of the current study. "Foreground occlusion" was accomplished by participants wearing a pair of tanning goggles with the protective lenses punched out. This is analogous to manipulating what the current author previously termed natural FOV. "Background occlusion" was accomplished by physically masking the HMD display with paper to permit a physical FOV of 60°, the same as the FOV of the tanning goggles. In this viewing condition, participants peripheral vision was not restricted, only the physical dimensions of the HMD display. The intent of the “foreground occlusion” was to have participants perceive the VE as background. Following exposure to each VE viewing condition, participants answered an in-house presence questionnaire.

Presence was revealed to be significantly higher in the “foreground occlusion” (Prothero et al., 1995). It has been suggested that when subjected to a vection stimulus, limiting FOV at the eye elicits more vection than compared to limiting FOV on the display or screen (Mergner & Becker, 1990). It can be inferred that participants may have felt more vection in Prothero et al.’s (1995) “foreground occlusion” condition, although it was not measured, and therefore as a result experienced more presence due to a more realistic visual stimulus in the VE. Prothero et al. (1995) suggested presence may be reduced by moving the boundary of a VE display away from the eye and also speculated that this may reduce SS.

The results of Prothero et al. (1995) are pertinent to the present study as a design aid as to how to manipulate FOV in the present study. It can be gathered by Prothero et al. (1995) that when restricting FOV in the current study, manipulation should take place so to not concurrently manipulate participants’ perception of background and foreground. Discrepancies as to what participants may perceive to be foreground or background may provide a confounding variable in the current study. Also, the work of Prothero et al. (1995) suggested presence may be higher when natural FOV is manipulated as compared to physical FOV of the display.

Unlike Lin et al. (2002) and Seay et al. (2001), an unpublished dissertation (Arthur, 2000) revealed no significant effects of FOV on presence. Arthur (2000) examined several physical FOVs on PQ scores while participants underwent performance tasks in an HMD VE. Statistically significant effects of physical FOV on presence were not revealed (Arthur, 2000). However, presence tended to increase with wider physical FOVs.

Present Study

The primary objective of the present study was to examine what physical and display characteristics of an HMD VE affect SS and presence. A secondary goal of the study was to identify any possible relationship between SS and presence. The overall purpose of the study was to expand the current research attempting to answer the overarching question, "What characteristics of HMDs make people sick?" Research is scarce in the investigation of interaction effects of HMD VE parameters. Previous research examining SS has been dominated by one-factor investigations.

One caveat existed in the current study which made it difficult to make strong inferences from previous research. Previous research has been driven by technological limitations and capabilities, rather than research questions. This has resulted in 2 problems: 1) inconsistency in stimuli and measures across studies and 2) seemingly mixed results.

The current research initially received its inspiration from DiZio & Lackner (1997) and has evolved from the attempt in replicating their work by using a "real" visual scene displayed to the user through an HMD. The rationale for replicating the research of

DiZio and Lackner (1997) without an artificially computer generated scene was simple; if update delay truly is the cause of SS, the same effect should be apparent when update delay is introduced to a real and natural image where large inherent update delays are not as much of a problem. To date, the author is not aware of any research investigating effects of update delay in a similar fashion (introducing update delay while viewing a live image). Furthermore, DiZio and Lackner (1997) only examined reduced FOV in one update delay condition. Therefore, it was of interest to further examine reduced FOV across multiple update delays and identify any interaction effects. From their study, it could be inferred that FOV and update delay have a prominent influence in the elicitation of SS, leading to hypothesized main effects of FOV and update delay on SS in the present study. Lastly, DiZio and Lackner (1997) provided the basis for the current experimental task.

The present study was a between-subjects 2X2X2 factorial design producing eight experimental conditions. The independent variables were levels of update delay, image scale factor, and peripheral vision. Levels of update delay were no additional delay (only minimal system update delay) and ~200 ms of additional delay. Levels of image scale factor were 2 and .88. Image scale factors were obtained by manipulating GFOV while holding the physical FOV of the HMD constant. Levels of peripheral vision were provided by the physical use, or lack of use, of “eye-cups” attached to the HMD display. “Eye-cups” were either attached to the HMD display resulting in peripheral vision occlusion, or were not attached resulting in external visual stimuli present in the periphery, or in other words, peripheral vision inclusion. The dependent variables measured in the current study were measures of SS, obtained by the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993), and measures of presence, obtained by the Presence Questionnaire (PQ, version 4.0; Witmer et al., 2005). Head movement positions along the yaw axis were also collected as a dependent variable to asses any potential systematic condition effects related to head movements. Head movement was operationally defined as movement of the head through rotation of the neck and, or torso.

Hypotheses

The present study hypothesized a main effect of update delay on SS. Even though previous research is inconsistent in revealing significant effects of update delay on SS, an update delay effect on SS was predicted. Some research has failed to reveal a significant effect of update delay on SS (Draper et al., 2001; Nelson et al., 2000; So, 1994), whereas other research has revealed the converse (DiZio & Lackner, 1997; Jennings et al., 2004; Wildzunas et al., 1996). Previous work from the current lab revealed a marginally significant update delay effect on SS (Moss et al., 2008). DiZio and Lackner (1997) and Moss et al. (2008), which are most similar to the design of the current study, revealed a difference in SS as a function of update delay, therefore providing rationale for the hypothesis.

A main effect of image scale factor on SS was hypothesized. This hypothesis was made based on DiZio and Lackner (1997), Seay et al. (2001), and Lin et al. (2002). DiZio and Lackner (1997) suggested SS to decrease when FOV (it is unclear if physical FOV or GFOV was manipulated) was reduced in half. Seay et al. (2001) and Lin et al. (2002) also revealed significant effects of FOV on SS. In addition, Draper (1998) and Draper et al.

(2001) revealed significant effects of image scale factor on SS. Although not statistically significant, in both studies (Draper, 1998; Draper et al., 2001), SS was greater with wider GFOVs.

A main effect of update delay on presence was also hypothesized in the current study. Barfield et al. (1998), Barfield and Hendrix (1995), and previous work in the current lab (Moss et al., 2008), similar to the current study suggested presence to be significantly less in higher update delay conditions as compared to lower update delay conditions. This supported the predicted main effect of update delay on presence.

A main effect of image scale factor on presence was hypothesized. The hypothesized main effect of image scale factor on presence was supported by Hendrix and Barfield (1996), Lin et al. (2002), Seay et al. (2001), which all revealed significantly higher presence with wider GFOVs, or FOVs as compared to narrower GFOVS, or FOVs. Previous unpublished work in the current lab suggested a significant effect of image scale factor on presence, with the greatest presence associated with the GFOV resulting in a consequential image scale factor closest to unity, or 1.

A main effect of peripheral vision on presence was also hypothesized. The rationale for predicting a main effect for peripheral vision on presence is not as straightforward. According to the construct of presence (Witmer & Singer, 1998), immersion is necessary to elicit presence. A more inclusive HMD VE can provide more immersion (Slater et al., 1996). A maximal, inclusive HMD VE can be described as one that isolates all external, real-world stimuli from the user, therefore, permitting all sensations to be provided by the HMD VE. Visual stimuli from the external environment are absent when peripheral vision is occluded. When peripheral vision is occluded, the only visual stimuli present are provided by the HMD VE. When peripheral vision is not occluded, the user is subjected to visual stimuli from the external environment, possibly providing less presence in the VE. Also, Prothero et al. (1995) revealed presence to be greater in a “foreground occlusion” condition as compared to a “background occlusion” condition. The “foreground occlusion” condition is similar to the reduction of external visual stimuli by occluding peripheral vision via the use of “eye-cups" in the current study. Lack of research relating to the physical characteristic of “eye-cups” on SS did not warrant a hypothesized main effect.

However, an interaction between peripheral vision and update delay on SS was hypothesized. It was predicted that more sickness would be reported when peripheral vision was occluded in the update delay conditions consisting of ~200 ms (in addition to inherent update delay) due to the thought that a greater degree of sensory conflict would exist between the visual and vestibular systems in these conditions. Update delay is the main source of a potential sensory conflict in the current study. Therefore, it was believed more conflict would exist when the “eye-cups” were attached, occluding maximal external peripheral vision in the current study. When the “eye-cups” are not attached, participants are still exposed to peripheral vision stimuli providing accurate visual motion cues congruent to vestibular motion cues during head movement. When the “eye-cups” are attached, occluding peripheral vision, the only visual motion cues provided are from the HMD display itself in central vision with the consequences of update delay.

CHAPTER III

METHOD

Participants

Participants consisted of 80 (30 males) individuals who responded to fliers around campus advertising the study. Participants were also obtained from the Psychology Department's subject pool via the Clemson University's Human Participation in Research (HPR) website. Data from 5 participants were discarded for various reasons (discussed below). Therefore, an additional 5 participants, matching gender of those who were discarded, completed the experiment to achieve the desired sample size of 80 participants. For those who were not discarded, participants ranged in age from 18 to 24 years, with a median age of 19 years. 71 participants were Caucasian, 8 were African-American, and 1 was Asian-Indian.

Participants were screened via a screening/demographic questionnaire to meet participation requirements prior to entering the laboratory. Individuals with any current or past self-reported heart, brain, visual (other than corrected vision), or inner ear ailments were not eligible to participate, as well as females who self-reported being pregnant. Individuals who had corrected vision and did not have or wear contacts were not eligible to participate. The HMD does not fit optimally for users who wear glasses. Individuals who self-reported experiencing MS often or easily were excluded from the study as well as individuals who participated in any previous HMD studies conducted in the laboratory. In addition, individuals with experience using HMDs were ineligible to participate. Eligible participants were asked to abstain from alcohol, tobacco, and caffeine up to 12 hours prior to the experiment. Participants were also asked to abstain from any vigorous physical activity prior to the experiment. Participants who were sick or feeling less than their usual state of well-being were asked to reschedule their participation. Participants who appeared to be sick or not well to the experimenter were sent home and rescheduled. Compensation for participation in the study was in the form of a financial payment of 10 dollars. Participants who signed up for the experiment via the HPR website received extra credit in an enrolled psychology course as well as the financial compensation.

Data collected from five participants were discarded due to various reasons. One participant was removed from the study because the participant reported moderate symptoms on several items, one of which was nausea, on the SSQ that was administered prior to donning the HMD before any practice trials began. This participant was not permitted to proceed any further, but did receive compensation. Another participant was not compliant throughout the entire experimental session. This participant would not remain still even after being reminded to do so repeatedly. This particular participant reported to have neglected to take ADHD medicine that day. At the completion of an experimental session, another participant reported to have extensive experience using HMDs even though the participant did not appropriately report this on the screening questionnaire. A fourth participant, who was a foreign national, had a difficult time understanding the experiment and as a result, was not very compliant. This participant paused several times during experimental trials to ask the experimenter questions and make irrelevant comments, resulting in erroneous head movements and the duration of the experimental session to last almost twice as long as any other participants' experimental sessions. Finally, a fifth participant failed to complete the practice trials and withdrew from the experiment before the start of the experimental trials.

Design

The present study was a 2X2X2 between-subjects factorial design consisting of eight conditions. Each condition consisted of 10 participants for a total of 80 participants. A between-subjects design was utilized to prevent any adaptation effects to SS.

Previous data collected in our lab in a similar study (Moss et al., 2008) regarding update delay and SS indicate an approximate effect size of .36. Therefore the current study would require approximately 34 participants per group to obtain adequate power for a one-tailed 2 group comparison (Friedman, 1968). Regarding image scale factor and SS, previous pilot data with similar levels of image scale factor indicate an approximate effect size of .53. This suggested a requirement for approximately 16 participants per group (Friedman, 1968).

Regarding update delay and presence, previous data collected in our lab (Moss et al., to appear 2008) indicate an approximate effect size of .90. Therefore the current study would require approximately seven participants per group to obtain adequate power for a one-tailed 2 group comparison (Friedman, 1968).

Main effect analyses for update delay on SS and presence, and image scale factor on SS should be adequately powered with 40 participants in each main effect group in the current study. Not enough is known regarding the use and disuse of “eye-cups” and any interaction effects to indicate a suggested sample size.

Based on our pilot data, the main effect of GFOV and presence may be under powered. However, as the other comparisons are adequately powered, we plan to use an N of 40.

The conditions of the current study were image scale factor, update delay, and peripheral vision occlusion. The levels of the image scale factor independent variable were 2 and .88. Image scale factors were obtained by the use of horizontal GFOVs of ~20° (image scale factor of 2) and ~45° (image scale factor of .88) while holding the physical FOV of the HMD constant at 40°. Recall that image scale factor is the ratio of physical FOV to GFOV (Physical FOV/GFOV). Most HMDs on the market today do not have physical FOVs exceeding 40° - 60° horizontal. The use of ~20° provided a narrower FOV, relative to typical FOVs of HMDs. The use of ~45° provided a FOV comparable to typical HMDs. Also, DiZio and Lackner (1997) reported significantly less SS when FOV was half as wide as compared to the widest FOV. It is unclear if GFOV or physical FOV was manipulated in DiZio and Lackner (1997).

Levels of update delay were minimal, inherent system delay (no additional update delay) and ~200 ms of additional update delay. Thresholds for detecting update delays have been reported to be as low as 14 ms (Mania et al., 2004) and as high as 322 ms (Allison et al., 2001). An update delay of ~200 ms falls within that range. Also, Moss et al. (to appear 2008) has suggested a marginally significant difference in SS between ~200 ms of additional delay and inherent system delay. DiZio and Lackner (1997) reported SS to increase in a consistent fashion as update delay increased and also used a delay of 200 ms in their reduced FOV condition.

Levels of peripheral vision were obtained by the use and disuse of “eye-cups.” “Eye-cups” are a physical characteristic of the HMD VE that can be attached to the HMD display to occlude peripheral vision from the external environment. According to Slater et al. (1996) and the Presence construct of Witmer and Singer (1998), occluding peripheral vision from the external environment created a more immersive HMD VE relative to visual stimuli from the external environment present in the periphery. The breakdown of conditions and their specific factor levels are listed in Table 3.1.

Table 3.1. List of conditions and respective factor levels.

Condition	Additional Update Delay	Image Scale Factor	Peripheral Vision
1	0 ms	2	Inclusion
2	0 ms	2	Occlusion
3	0 ms	.88	Inclusion
4	0 ms	.88	Occlusion
5	~200 ms	2	Inclusion
6	~200 ms	2	Occlusion
7	~200 ms	.88	Inclusion
8	~200 ms	.88	Occlusion

The dependent variables of the study were simulator sickness (SS) as measured by the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993) and presence as measured by the Presence Questionnaire (PQ, version 4.0; Witmer et al., 2005). A third dependent variable was measurement of head movements. Head position data were obtained by a head tracker. Head movements were measured to asses any systematic condition effects related to head movements.

Participants were pseudo-randomly assigned to a condition based on a sequence of conditions derived by a random number generator. However, since there was an anticipation of more females in the sample due to the fact that more female students are enrolled in psychology courses than males at Clemson University, the experimenter ensured that male participants were not unequally distributed among the conditions. Each condition consisted of four male and six female participants with the exception of conditions 1 and 8. Conditions 1 and 8 consisted of 3 males and 7 females.

The study was approved by the Clemson University Institutional Review Board. Participants completed a Clemson University Institutional Review Board approved consent form prior to the study that indicated the background of the experiment, potential benefits and risks of participation, and the procedure that followed. It was also made known to the participants that they had the option to discontinue participation at any time, for any reason, and without penalty.

Materials

A consent form, demographic questionnaire (See Appendices A and B), and the Motion Sickness History Questionnaire (MSHQ; Reason, 1968, as cited in Reason & Brand, 1975) were distributed to the participants prior to any experimental sessions. The SSQ and PQ were administered to obtain measures of the dependent variables, SS and presence. Other materials used in the present study were provided by Dr. Eric Muth and his Human Stress and Motion Science Laboratory in the Psychology Department of Clemson University. These included the HMD, video camera, camera lens, and "eye-cups." The capability for update delay manipulation in the current study was provided by an in-house software program. Tom Epton, a graduate student in the Electrical and Computer Engineering Department of Clemson University, developed the software program.

Motion Sickness History Questionnaire

The Motion Sickness History Questionnaire (MSHQ) was developed by Reason (Reason, 1968, as cited in Reason & Brand, 1975) as a subjective MS measurement. See Appendix C. More specifically, the MSHQ is most often used today as an assessment of MS susceptibility. The MSHQ obtains measurements of how often one has been exposed to a particular type of transportation (i.e. cars, trains, boats, and others), if that type of transportation caused MS in the past, frequency of experienced MS due to that type of transportation, and if the experienced MS resulted in emesis. The resulting output of the MSHQ is a single value indicating susceptibility to MS. A greater value indicates more susceptibility. The MSHQ was administered for a potential post-hoc analysis in order to identify any possible participant outliers in respect to MS susceptibility. Archived data in our laboratory, collected from a sample of 750 college aged students (429 males), has revealed a mean MSHQ (± standard deviation) of 27.58 (± 22.37).

Simulator Sickness Questionnaire (SSQ)

The SSQ was developed by Kennedy et al. (1993) out of a need for a more appropriate and valid measure to assess MS-like symptoms observed as a result of exposure to simulators (i.e. SS). A copy of the SSQ is located in Appendix D. Prior to the SSQ, the Pensacola Motion Sickness Questionnaire (MSQ) that was developed over 25 years ago was most often used to measure SS (Kennedy et al., 1993). Before the advent of simulators, the MSQ was used as a subjective report of MS experienced from more typical and provocative motion stimuli (e.g. Naval ships and seasickness; Kennedy et al., 2003).

The SSQ was developed from data drawn from more than 1,100 MSQs collected from exposure across 10 Navy simulators (Kennedy et al., 1993). The MSQ contained 28 items, or symptoms. From these 1,100 plus MSQs, items that were reported with less than 1% frequency were removed, leaving 16 items. A series of factor analyses were then performed on these items, resulting in the 16 item SSQ containing three subscales. The subscales are oculomotor symptoms, disorientation symptoms, and nausea symptoms (Kennedy et al., 1993). The oculomotor subscale includes symptoms of eyestrain, difficulty focusing, blurred vision, and headache. The disorientation subscale includes symptoms of dizziness and vertigo. The nausea subscale includes symptoms of nausea, stomach awareness, increased salivation, and burping.

Participants respond to the 16 items of the SSQ by indicating how severe they experienced each one of the symptoms at the time of SSQ administration on the scale of “none, slight, moderate, or severe,” obtaining a raw score of ‘0,’ ‘1,’ ‘2,’, or ‘3,’ respectively, for each item of the SSQ. According to Kennedy et al. (1993), the SSQ assumes the screening of “unhealthy” participants as well as, “individuals in other than their usual state of fitness are eliminated from the sample (p. 211).” The output of the SSQ is a Total Severity (TS) score, or total score, and three subscale scores. Each subscale score is a summation of raw scores within the particular subscale multiplied by a constant specific to the subscale. The TS score is a weighted score obtained by the summation of the subscales’ raw scores multiplied by a constant to indicate overall sickness levels experienced in a VE. The reader is directed to Kennedy et al. (1993) for more information regarding how the abovementioned constants were derived. The subscales serve as a diagnostic tool to compare and contrast varying VEs in order to indicate which specific aspects of VEs are problematic and need to be addressed (Kennedy et al., 1993). The current study was interested in overall sickness levels and therefore, TS scores will be analyzed. The current study was not interested in diagnosing and addressing problematic VE platforms.

In order for a questionnaire to be useful and meaningful, it has to demonstrate reliability and validity. Without going into a full discussion of reliability and validity, reliability refers to how consistent a questionnaire measures what it is intended to measure. A simple example of a type of reliability is test-retest reliability. If a test demonstrates test-retest reliability, a score obtained at two different times will be consistent. E.g., a reliable IQ test will produce consistent results taken at 20 years of age and 21. Whether or not a questionnaire actually measures what it is intended to measure is its validity. E.g., a SS questionnaire *should* measure SS if valid, and not spatial ability.

A questionnaire (e.g. SS) may demonstrate reliability, but if it consistently measures something that the questionnaire is not intended to measure (e.g. spatial ability), the measure is meaningless.

The SSQ, which is currently the predominate measure of SS, has demonstrated validity and reliability. Recall that the SSQ was derived by using the MSQ to measure MS symptoms resulting from simulator exposure from over 1,100 observations. The 28 item MSQ was shortened to the 16 item SSQ by removing infrequently (less than 1%) reported symptoms of the MSQ (Kennedy et al., 1993). Therefore, the SSQ demonstrates content validity since it is measuring MS symptoms that were observed from simulator VE exposure. A series of factor analyses were further performed to quantify the content validity of the SSQ. The reader is directed to Kennedy et al. (1993) for further discussion on the series of factor analyses that were performed. Reliability or the consistency of the SSQ measure has been demonstrated by a strong split-half correlation of 0.80, corrected to 0.89, from SSQs obtained from 200 participants (Kennedy, Stanney, Compton, Drexler, & Jones, 1999, as cited in Kennedy et al., 2003). Split-half correlations demonstrate to what degree two equally divided parts of a questionnaire correlate with one another. Split-half reliability measures, rather than test-retest reliability, is used in such circumstances because of potential habituation, or adaptation effects. A similar strong reliability correlation of 0.78 was found from exposure to a driving simulator (Yoo, 1999, as cited in Kennedy et al., 2003). The widely accepted and predominate use of the SSQ to measure SS (permitting consistent comparisons across studies), its reliability and content validity, and the fact that is was derived from a large sample of over 1,100 MSQs are strengths of the SSQ. Kennedy et al. (1993) briefly point out one deficiency of the SSQ. Items within subscales should be homogenous (i.e. subscales should be independent), however the subscales are correlated higher with each other than is optimal (Kennedy et al., 1993).

Although the SSQ was developed from exposure to simulator VEs, the SSQ is still the primary measure of SS for all types of VEs, including HMD VEs. The average total SSQ score for simulator VEs has been reported to be 10, whereas the average total SSQ score for other VEs (i.e. HMD VEs) has been reported to be above 20 (Stanney & Kennedy, 1997; Stanney, et al., 1997). Minimally, one may obtain a total score of above 20 by responding “slight” to only three items on the SSQ. Furthermore, according to Stanney et al. (1997), total SSQ scores of 5-10 represents minimal symptoms, 10-15 represents significant symptoms, 15-20 represents severe symptoms, and above 20 is indicative of a bad and problematic simulator VE. However, it is noted that this categorical breakdown was derived from 1,000s of SSQs obtained from exposures to flight simulators, and not HMD VEs.

Presence Questionnaire (PQ, version 4.0)

The Presence Questionnaire (PQ, version 4.0; Witmer, Jerome, & Singer, 2005) was used to measure the subjective experience of feeling as if one is in another environment while physically located in a separate environment, i.e. the feeling of being in the VE at the same time of being situated in the real-world. The PQ has gone through several iterations since the first version of the PQ (Witmer & Singer, 1994, as cited in Witmer & Singer, 1998). The current PQ (version 4.0) was derived from a series of factor and reliability analyses of PQ (version 3.0, Witmer & Singer, 1998) data from 325 participants who were exposed to VEs (Witmer et al., 2005). A four-factor model with 29 items emerged as a better fit to the data than the previous PQ's (version 3.0) six-factor model.

The four subscales represent aspects that lead to the experience of presence. These subscales are involvement, sensory fidelity, adaptation/immersion, and interface quality. Internal consistency reliability coefficients (Cronbach's alpha) revealed alpha values of .89, .84, .80, and .57 for each factor of involvement, sensory fidelity, adaptation/immersion, and interface quality, respectively (Witmer et al. 2005). The reader is directed to Witmer et al. (2005) for further explanation of the development of the PQ, version 4.0.

The differences between version 3.0 and version 4.0 of the PQ are not substantial. Version 3.0 contained six subscales for a total of 32 items, whereas version 4.0 contains four subscales for a total of 29 items. All the items in 4.0 are the same as were in 3.0, with the only exception being the 3 items that were removed from 3.0. Furthermore, the researcher of the current study was not aware of any related research that has mentioned, analyzed, or reported subscale scores. Research has only obtained and reported total PQ scores.

Participants respond to each item on the PQ by placing an "X" along a seven point likert-scale. See Appendix E for the items on the PQ and the dimensions of the likert-scale. Corresponding to where on the likert-scale a response is recorded, a score ranging from 1-7 is obtained for each item on the PQ. Several items require reverse scoring (items 19, 22, 23). A total PQ score is then obtained from summation of all 29 items. Currently, range of scores constituting degrees of presence is not known.

The PQ (version 4.0; Witmer et al., 2005) has strengths and weaknesses in the assessment of presence. A strength of the PQ (version 4.0) is that it has been derived from several iterations of previous versions of the PQ (Witmer & Singer, 1994, as cited in Witmer & Singer, 1998; Witmer & Singer, 1998), which has reanalyzed the internal consistency reliability throughout the iterations. As aforementioned, moderate to strong internal consistency reliability coefficients of each factor of the PQ (version 4.0) has been demonstrated. Another demonstration of the current PQ’s reliability is that a series of factor analyses identified three of its four factors to be similar to the PQ (version 3.0). A second strength of the current PQ, as with previous versions of the PQ, is that it is a comprehensive and multidimensional measure rather than an in-house questionnaire containing a few homogenous items attempting to measure presence (Witmer et al., 2005). The PQ contains factors that are believed to contribute to the overall construct of presence (i.e. involvement, sensory fidelity, adaptation/immersion, and interface quality).

The PQ does have its weaknesses. An underlying weakness of the PQ, also mentioned in Witmer et al. (2005), is that the concept of presence is relatively immature, requiring all measures of presence to be further analyzed to obtain confidence in its validity. A second weakness to the PQ is that its criterion validity needs to be addressed. Criterion validity refers to determining validity of a measure by examining the measure against an established criterion. An example of criterion validity is the examination of a MS questionnaire against an objective, psychophysiological measure of MS. A third weakness of the PQ is the assessment of its content validity. The PQ's content validity was discussed in Witmer and Singer (1998). The PQ's content validity is based on theoretical relationships and not consistent empirical findings. For example, according to Witmer and Singer (1998), SS and presence should have a negative relationship since the experience of heightened SS should draw attention away from the VE and towards the experienced SS, decreasing involvement in the VE. Witmer and Singer (1998) revealed a significant correlation between SSQ scores and PQ scores of $r = -0.426$ across four experiments. However, research examining the relationship between SS and presence is inconsistent. Seay et al. (2001) failed to demonstrate a significant relationship between SS and presence; Moss, Walker, Carpenter, and Muth (2007) suggested a statistically non-significant positive relationship; and Lin et al. (2002) suggested a significant positive relationship. Also, Kennedy et al. (2003, p. 251) suspect an increase in SS when level of "realism" is increased. The reader is directed to Witmer and Singer (1998) for further rationale for the validity of the PQ.

In all, the PQ (version 4.0; Witmer et al., 2005) was chosen as a presence measure because the PQ itself has been investigated in the literature (although, as admitted by Witmer et al., 2005, further investigation is necessary and is ongoing) and has been the measure of presence used in prior studies completed in our laboratory, permitting consistent comparisons across studies. Although the PQ does have several weaknesses, for the strengths discussed above and the relatively young concept of presence, the current researcher believes the PQ is the best available measure of presence at the time of the current study.

Even though participants answered all 29 items of the PQ (version 4.0), several items of the PQ were not included in total PQ scores. The items that were dropped were items 5, 6, 11-17, 21, 23, 24, 29, 31, and 32. These items were deemed irrelevant and not useful in obtaining a measurement of presence with respect to the specific HMD VE task in the current study. For example, item 13, “How well could you actively survey or search the virtual environment using touch?”, was removed since participants did not have the ability to search the VE using touch.

Helmet Mounted Display (HMD)

A Kaiser Electro-Optics, Inc., *ProView™ XL 50* HMD designed for professional applications was used in the study. “Eye-cups” specifically for the *XL 50* were also provided. Two separate “eye-cups” were made to be attached and to be removed from each display of the HMD. The “eye-cups” occlude peripheral vision from the external environment. The “eye-cups” are rubber-like moldings. The HMD without “eye-cups” attached can be seen in Figure 3.1. The HMD with “eye-cups” attached can be seen in Figure 3.2. The “eye-cups” alone can be seen in Figure 3.3.

The physical display of the HMD was 50° diagonal, 30° vertical, and 40° horizontal. Resolution of the HMD was 1024 x 768. The frame rate of the HMD was 60 Hz. The weight of the HMD before camera mount was 35 oz. The HMD provided multiple adjustments for an optimal fit. Although monoscopic imagery was used in the study, the HMD provided capabilities for both stereoscopic and monoscopic imagery.

Figure 3.1. HMD without “eye-cups” and mounted video camera.

Figure 3.2. HMD with “eye-cups” and mounted video camera.

Figure 3.3. “Eye-cups” alone.

Video Camera

A Uniq *UC-610CL* color digital CCD camera link camera was used to capture real, live images in the study. The camera can be seen mounted to the HMD in Figures 3.1 and 3.2. A close up of the camera can be seen in Figure 3.4. The camera had a resolution of 659 x 494 active pixels and a frame rate of 110 Hz. The CCD sensor of the camera was a 1/3” progressive scan with R, G, and B primary color mosaic filters. The lens mount platform was C-mount. The weight of the camera was 200 g. The camera was mounted on the HMD to view a real video display of the laboratory. The camera was mounted on the HMD using a light piece of aluminum epoxied to the HMD.

Figure 3.4. Close up of the camera as mounted on the HMD.

A Dalsa *X64 CL Express*™ *PCI* camera link frame grabber was used for image capture and was installed on a *Windows XP* computer with a 3.2 Ghz *Pentium IV* processor and 2 Gb of RAM. The scene captured by the camera and displayed via the HMD was also displayed to the experimenter on the computer monitor. The video card was a 256 Mb *PCI Express*™.

Update Delay Software

Tom Epton, a graduate student in the Electrical and Computer Engineering Department of Clemson University, developed the software program that permitted update delay manipulation. The programming library for image acquisition and control used to develop the software was Dalsa's *Sapera*™ *LT*. *Sapera*™ *LT* is based on a set of

C++ classes. The following is a description of how the program introduced additional update delay in the system (Tom Epton, personal communication):

> The camera operates at 110 Hz and therefore captures an image every 9.09 ms. Rather than immediately displaying the captured image, it is placed in an internal buffer. The amount of delay that is added to the system depends on how many images are placed into the buffer. For example, to add in 27 ms of delay, three consecutive captured images from the camera are placed into the buffer. When the 4th image is placed in the buffer, the first image is removed and displaced, leaving three images remaining in the buffer. In other words, as soon as the number of images is placed into the buffer to satisfy the delay amount, the buffer then acts like a queue with FIFO (First In First Out) ordering. When a captured image is placed at the tail of the queue, the image at the head of the queue is removed and displayed.

In the current study, 22 frames were inputted in the program to obtain ~200 ms (22 X 9.09 ms = ~200 ms) of additional update delay for the update delay condition.

Camera Lens

The C-mount lens used in the study was a 1/2” format Tokina *TVR0614* varifocal lens. The manual varifocal length was 6-15 mm. The horizontal FOV provided by the lens listed in the technical specifications ranged from 19° - 44°. The aperture of the lens was 1.4.

Although the horizontal FOV of the lens was listed in the technical specifications, technical specifications for FOV are often inaccurate. Therefore, FOV measurements were verified by “hand” using simple, right triangle trigonometry. A distance measurement was obtained between the camera and a large poster board. A mark was made on the poster board directly in front of the camera. A mark was made on the poster board where an object just came into view on the right side of the camera and distance was measured between this mark and the mark in front of the camera. The two distance measurements were used to obtain the angle of view between the camera and the maximum viewing distance to the right. The same procedure was followed for the angle of view to the left of the camera. The summation of the two angles provided the horizontal FOVs of the camera listed in the current study. The same procedure was used to obtain the vertical FOV of the camera. This overall procedure was repeated several times to insure measurement accuracy. Horizontal FOV verified by hand was ~20° and ~45°. Vertical FOV was ~15° and ~33°, respectively.

Head Tracker

The Ascension Technology Corporation’s *3D-BIRD*^{TM} head tracker was used to obtain head movement measurements along yaw, pitch, and roll axes. The *3D-BIRD*^{TM} is used to track three degrees of orientation of any object it is attached to in real time. Orientation is measured from outputs obtained by solid-state inertial and non-inertial sensors. The head tracker was attached to the HMD. The angular range capability of the head tracker is ± 180° yaw, ± 90° pitch, and ± 180° roll with a dynamic accuracy of 4.0° rms. The sampling rate of the head tracker is 160 Hz.

Room Layout

Participants had to search and locate eight objects in the laboratory during experimental conditions. These objects were a clock, curtain, flag, fire extinguisher, fan, front door, office door, and first aid kit. See Figure 3.5 for a layout of the objects within the Human Stress and Motion Science Laboratory. The front door, office door, and curtain were marked with an "X" to indicate what constituted each respected object. See Figure 3.6 for pictures of the objects. An Olympus *Pearlcorder S702* microcassette recorder was used to record sequence of object search during the experimental sessions.

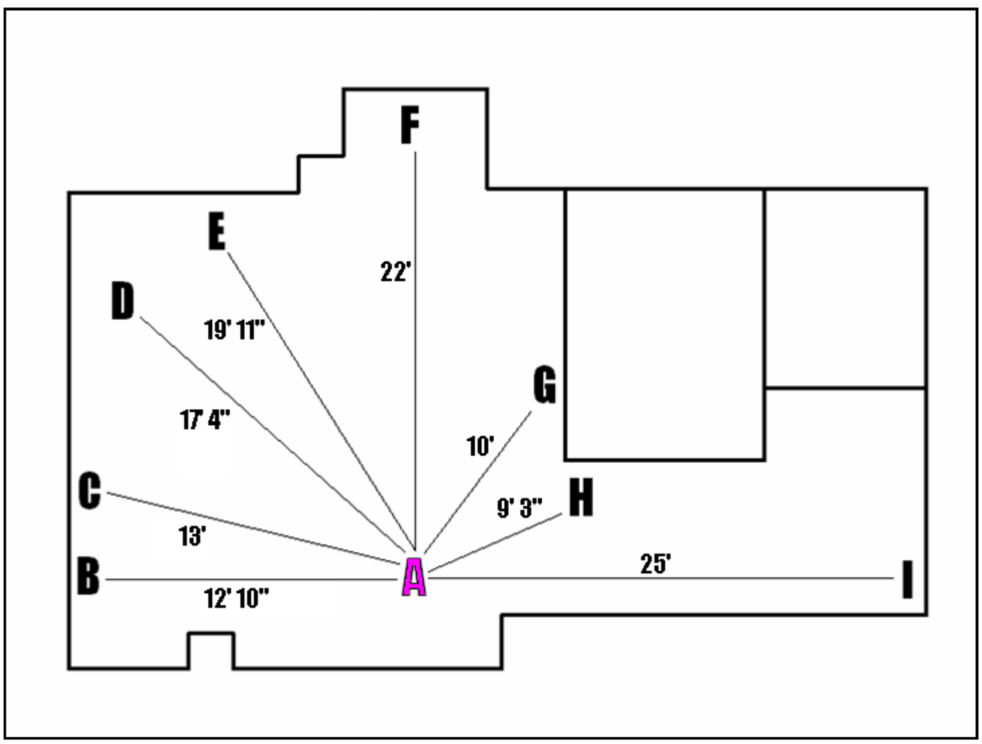

Figure 3.5. Object/room layout with distance measurements from participant. A = participant, B = office door, C = clock, D = flag, E = fire extinguisher, F = front door, G = first aid, H = fan, I = curtain.

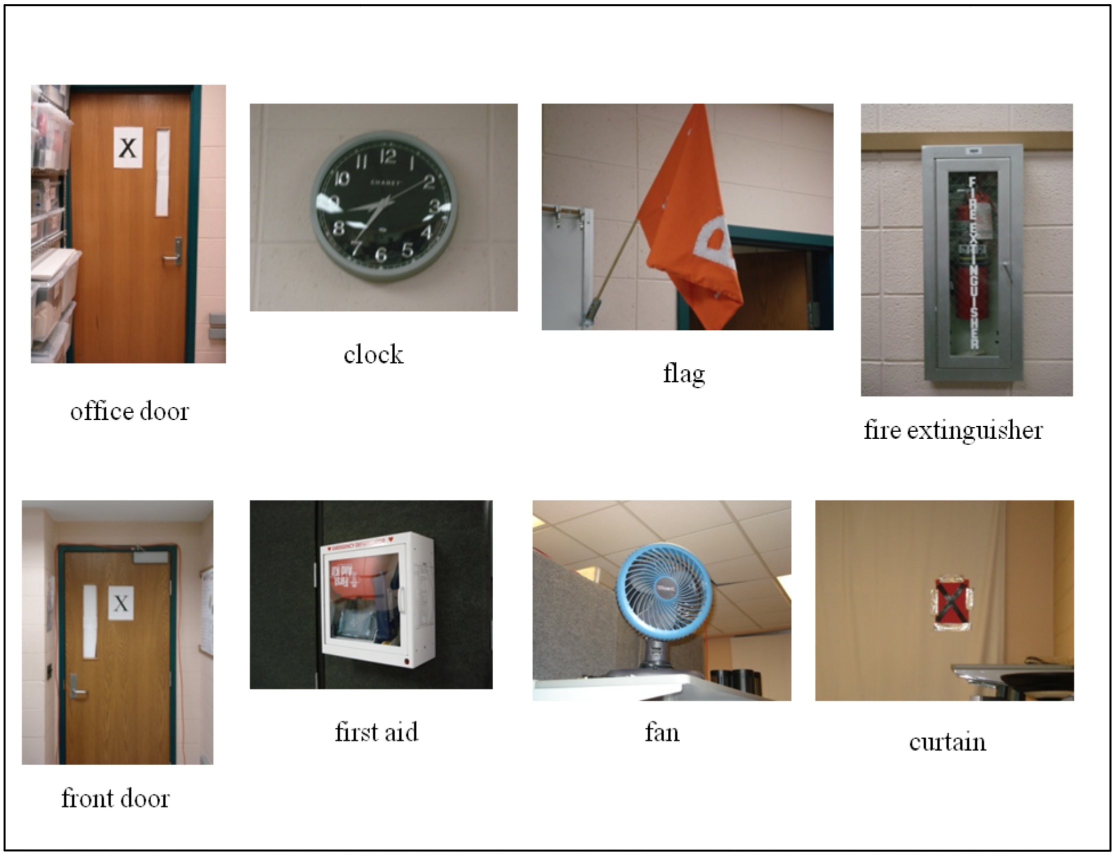

Figure 3.6. Pictures of the objects participants searched for in the current study.

Procedure

Before participants arrived to the laboratory, the video camera and HMD were powered on, and the proper focal adjustment was made on the lens corresponding to the GFOV necessary to obtain the desired image scale factor of the current experimental condition. Also, “eye-cups” were attached or removed (peripheral vision occlusion and inclusion, respectively), depending on the current experimental condition. Lastly, update delay of ~200 ms was input in the program if the current experimental condition included additional update delay. Upon arriving to the lab, participants completed and signed a consent form, demographic questionnaire, and the MSHQ. Participants were then instructed to turn off their cell phones and to remove any outerwear (i.e. jackets, fleeces, or sweatshirts).

Prior to the experimental conditions, participants were briefed on the experimental task and the objects within the laboratory were pointed out. Participants made active head movements about the yaw axis while standing to perform a simple visual search task. Participants were instructed that they were to simply locate each object that was called out by the microcassette recorder. Participants were told to center each object within the display. They were also informed that the voice recording would specify the direction of head movement (e.g. "left, office door"). Direction of head movement was given to prevent any unnecessary erroneous head movement. They were instructed to stand still with feet facing forward at all times and only make head movements with their head and neck, and torso, if necessary. Participants were informed not to make any movements with their lower body. In addition, participants were instructed to stand comfortably without locking their knees while keeping their hands and arms to their sides and out of any pockets. Participants were once again reminded to only make head movements when instructed by the voice recording or by the experimenter. Participants indicated comprehension of the experimental procedure and knowledge of object location before beginning.

Participants were then directed where to stand during the experimental session. Prior to donning the HMD, participants were given a verbal overview and demonstration on how to adjust the HMD for optimal fit. The experimenter assisted the participants in donning the HMD. The participants made the necessary adjustments for optimal fit and the experimenter ensured that the HMD was securely donned. Once donned, participants viewed an eye chart and proper adjustments were made to the lens to ensure image clarity.

Each participant completed a set of two abbreviated practice trials before the experimental session. The practice trials consisted of the current experimental sessions' conditions. Each practice trial was 48 s in duration permitting each object to be located twice. To ensure standardized frequency of head movements, the microcassette recorder instructed head movements at 3 s intervals. The SSQ was administered verbally to the participant before the set of practice trials without donning the HMD and once following the set of practice trials, while donning the HMD. The SSQ was pre-recorded on a microcassette recorder by another member of the laboratory, not the experimenter, to ensure a neutral tone and to prevent any potential response expectancy bias. The experimenter recorded participants' responses to the SSQ on a hardcopy of the SSQ.

Following the set of practice trials, the experimental session began. Each experimental session consisted of a sequence of 200 randomized head movements blocked into five, two-min trials. The identical sequence of 200 randomized head movements was used for each participant. A one-min break existed between each trial. Forty head movements were made during each trial with an approximate frequency of 3 s per head movement. See Appendix F for the sequence of head movements for each trial. Participants stood facing straight ahead and viewed the "front door" to start the experimental session. At the end of each trial, participants returned to the start position ("front door") for the one-min break interval and were instructed to keep their head forward and to remain still. Participants remained standing and continued to don the HMD.

The experimenter viewed a computer monitor that displayed the same image the participants viewed. To ensure the participants were performing the task correctly, the participants had to approximately center the object in their view. Also, the experimenter noted the following occurrences: the participant viewed the wrong object, the participant overshot an object (i.e. swept past the object and had to return in the opposite direction), the participant initially made a movement in the wrong direction, and the participant was lost and could not locate the object before the next object was called. See Appendix F for the "head movement accuracy checklist." In addition to the subjective "head movement accuracy checklist," a head-tracker collected head movement data. The head-tracker was enabled immediately prior to the start of the practice trials.

The SSQ was administered and completed by the participants during the one-min break intervals following trial 1, trial 2, trial 3, and trial 4. The SSQ was again completed immediately after trial 5. After the completion of the SSQ following trial 5, the head-tracker was disabled. At this time, participants removed the HMD and sat for 10 min. Immediately after removing the HMD and once seated, participants completed a written PQ. Participants were instructed to read the instructions of the PQ and to answer in regards to the experience while donning the HMD performing the experimental task. In addition, participants were instructed to, "give the best possible answer considering the situation you were in." The SSQ was again verbally completed after 5 and 10 min. In summary, the SSQ was administered before and after the set of practice trials, after trials 1-5, and 5 and 10 min after experimental session completion for a total of nine SSQs per participant.

Participants were then debriefed and compensated for their time. Participants were free to leave the laboratory if there were not any observed signs of noticeable (via SSQ or visually) residual SS. If there were observed signs of residual SS post 10 min, participants completed an additional SSQ every 5 min and were asked to remain in the laboratory until the experimenter felt SS subsided to a comfortable level. The duration of the experimental session in which participants donned the HMD was ~20 min. The time the participants entered the laboratory to the time the participants left the laboratory lasted ~1 hr.

A minor change to the experimental procedure was implemented after the 28th participant completed the experiment due to an unexpected observation. Seven out of the first 28 participants (25%) withdrew from the experiment in its entirety due to nausea and faint-like symptoms. This frequency was unexpected based on three prior studies performed in our laboratory, encompassing 80 participants in all, which utilized a similar paradigm as the current study. Only 2 participants out of the previous 80 terminated participation prematurely. This observation called for the experimenter to reexamine any differences between the previous studies and the current study that may offer a possible explanation for the unexpected observation. The only apparent difference was that a step ladder, which came up to about waist-height, was placed in front of the participants in the previous studies. The participants had the option to grasp onto the back of the step ladder to ensure balance, if necessary. To the best of the experimenter's recollection, most, if not all, participants grasped onto the back of the step ladder throughout the experimental sessions.

However, the current study's design did not initially permit participants to grasp onto anything. Participants stood freely with their hands and arms down to their sides while making active head movements. Therefore, based on the aforementioned difference, the frequency of withdrawal, and safety precautions, a decision was made to embed the use of the step ladder in the experimental design. An additional 12 participants completed the experiment without grasping the back of the step ladder while 40 participants grasped the back of the step ladder with both hands, thus providing an equal amount of participants who did and did not grasp the step ladder. Overall, there were five participants in each condition with and without the use of the step ladder. Hereafter, the step ladder will be referred to as 'hand-rail.'

Data Analyses

Data Reduction

The peak (i.e. highest) SSQ score from each participant were used to examine SS. Nine SSQ scores were obtained from each participant (before and after practice, after trials 1-5, and after 5 and 10 min). Peak SSQ scores were used in case of circumstances in which a participant may have withdrawn from the study prior to completing all five trials. The rationale for this was the assumption that the SSQ score obtained at the time of participant withdrawal would be the highest. Therefore, a SSQ score would be obtained and used from all participants, regardless if they completed all experimental trials, leaving the analyses without any missing SSQ data.

Total PQ scores were used to examine presence. In the case of participant withdrawal, the PQ was administered at the time of withdrawal to ensure PQ data from all participants.

Participants were also divided into ‘sick’ and ‘not sick’ groups based on a median split of peak SSQ scores from all 80 participants. Those participants who had a peak SSQ score below the median were placed into the ‘not sick’ group. Those participants who had a peak SSQ score above or equal to the median were placed into the ‘sick’ group. This procedure has been previously utilized in our laboratory in the examination of SS (Walker, 2008).

Head movement position data required reduction in the current study and were reduced in a similar fashion as in Walker (2008) using a program designed in Matlab (The Mathworks, Inc., Novi, MI). The head tracker output head movement positions about the yaw, pitch, and roll axes sampled at 160 Hz. Only head position data about the yaw axis were extracted for analyses because the predominate movement required to search for the objects in the current study was about the yaw axis. The first step in head position data reduction was the removal of data obtained during the practice trials. The elapsed time between the enabling of the head tracker and the start of the experimental trials for each participant was ~ 4 min. At a sampling rate of 160 Hz, 38,000 data points represented ~ 4 min. and therefore, the program removed the first 38,000 data points from each data file. Each data file was then down sampled by the program to 10 Hz.

Absolute values of the differences between each data point were then obtained, which represented the absolute differences between consecutive head positions at 10 Hz, or every 100 ms. In addition, the program discarded all differences less than 1° per 100 ms. Differences of less than 1° per 100 ms were defined as epochs during the experimental task in which there were no head movements, which was not pertinent to the current study. The end result of data reduction was an average of the differences between consecutive head positions for each participant, which was then multiplied by 10 to obtain an average head movement velocity in degrees per second.

Statistical Tests of the Hypotheses

A series of two, 2 (update delay) X 2 (image scale factor) X 2 (peripheral vision occlusion) between- subjects ANOVAs were performed to analyze the hypothesized main effects and interaction of the current study. Main effects of update delay and image scale factor were predicted on SS. In addition, an update delay X peripheral vision occlusion interaction was predicted on SS. A second 2 (update delay) X 2 (image scale factor) X 2 (peripheral vision occlusion) between-subjects ANOVA was performed to analyze the hypothesized main effects of update delay, image scale factor, and peripheral vision on presence. There were no hypothesized interaction effects regarding presence. Measures of SS and presence were obtained by SSQ and PQ scores, respectively. All effects were statistically significant at the .05 significance level.

Exploratory Analyses

The following analyses described hereafter were performed to examine relationships in which the current dissertation did not make specific hypotheses. The Pearson's bivariate correlation was performed to identify any relationship between peak SSQ and PQ scores. The secondary goal of the current study was to examine the relationship, if any, between presence and SS. All effects were statistically significant at the .05 significance level.

A series of three, 2X2 chi-square analyses were performed for each factor (update delay, image scale factor, and peripheral vision occlusion) of the current study between 'sick' and 'not sick' groups to explore the dependence of participants' sickness levels within each factor. Participants were partitioned into a 'sick' and 'not sick' group based upon a median split. The median peak SSQ score obtained in the current study (n=80) was 26.18. Participants whose peak SSQ score was below 26.18 were split into a 'not sick' group and those whose peak SSQ score was above or equal to 26.18 were split into a 'sick' group, leaving 39 participants in the former and 41 participants in the latter. In addition, the median peak SSQ score obtain from all previous related studies (Moss, Scisco, & Muth, in press; Moss et al., 2008) conducted in our laboratory, including the current study, was 26.18 (n=160). Furthermore, in a study examining SS and HMDs, Moss et al. (2007) obtained a median peak SSQ score of 22.44. According to Stanney et al. (1997), a SSQ score of above 20 is indicative of a bad simulator. Therefore, supported from the abovementioned, the split of participants into 'sick' and 'not sick' groups based on a median split at a peak SSQ of 26.18 was reasonable in order to obtain a dichotomous measure of sickness. To date, the current researcher is not aware of any empirical findings to suggest what score across the continuous scale of the SSQ constitutes an individual to be simulator sick as a result to HMD VE exposure. Even though Stanney et al. (1997) categorized a SSQ score of above 20 as indicative of a bad simulator, the data obtained to derive such a categorization was from flight simulators.

An additional 2X2 chi-square analysis was performed between those participants who withdrew and did not withdraw from the experiment between those participants who grasped and did not grasp the hand-rail to explore the dependence of the use of the hand-rail on participant withdrawal.

A 1 (participant) X 9 (trial) repeated measures analysis of variance was performed to explore any effects of trial (i.e. time) on SS. Post-hoc pairwise comparisons were performed where appropriate. SSQs were administered pre practice, post practice, after experimental trials 1-5, 5 min post exposure, and 10 min post exposure for a total of 9 SSQs. Trial was operationally defined as time of SSQ administration.

Any systematic condition effects related to head movements were analyzed by performing a 2 (update delay) X 2 (image scale factor) X 2 (peripheral vision occlusion) between-subjects analysis of variance. The investigated measure was head movement velocity. In addition, the Pearson's correlation was employed to examine the relationship between head movement velocity and SS (i.e. peak SSQ scores). The goal of these analyses was to examine the existence of any differences in head movements between conditions as well as to identify any relationship between SS and head movements.

CHAPTER IV

RESULTS

Usable data sets were collected from 80 participants. Out of those 80 participants, 7 participants (6 female) withdrew from the experiment before completion of all 5 experimental trials due to sickness and other extreme responses. Three (1 male) of these seven participants who withdrew reported ‘typical’ sickness responses such as dizziness and nausea. One participant fell short of full emesis and spat into a sickness bag. However, four of the remaining participants who withdrew appeared to have a response distinctive from the other three ‘typical’ sickness responses. These four participants (4 female) experienced faint-like responses, increased warmth, confusion, ataxia, and tunnel vision. All four of these participants required the experimenter to physically assist them to a seated position in a nearby recliner. During debriefing, these four participants reported to never have had similar experiences or experienced MS in the past and that the experienced sensations came on abruptly. Additionally, they reported to have felt close to fainting or ‘passing out.’ Furthermore, these participants reported confusion in that they could hear the experimenter but not understand the experimenter. Some responses from these participants immediately prior to withdrawal were, “I can’t see,” “everything is black,” “I’m getting very hot,” “I’m going to throw up,” and, “I’m going to pass out.” All of those seven participants who did withdraw from the experiment participated before the implementation of the hand-rail, thus did not grasp the hand-rail during the experiment. Peak SSQ and PQ scores, as well as head position data were collected from these participants during their abbreviated participation.

A frequency distribution of peak SSQ scores obtained from all 80 participants revealed three problems. See Figure 4.1 showing a histogram of peak SSQ scores. One problem was a problem with the normality of the distribution. The distribution of the peak SSQ scores was positively skewed. The second problem was heterogeneity of variance. Variances between conditions were not equal. The condition with the greatest amount of variance (condition 4) and the condition with the least amount of variance (condition 3) differed by a factor slightly above 13. See Appendix G for histograms of peak SSQ scores for each condition. The third problem was that three extreme peak SSQ scores were identified. These peak SSQ scores were 164.56, 172.04, and 183.26. Only one of these peak SSQ scores was obtained from a participant who withdrew. An examination of all peak SSQ scores obtained from related studies (n=80) conducted in our laboratory (Moss, Scisco, & Muth, in press; Moss et al., 2008) revealed no peak SSQ scores at or above 150. In addition, the use of the interquartile range ($Q_3 – Q_{1;}$ 48.62) of peak SSQ scores obtained in the current study and Q_3 + (1.5×IQR) to indicate extreme values and potential outliers suggested scores of above 129.03 to be extreme values.

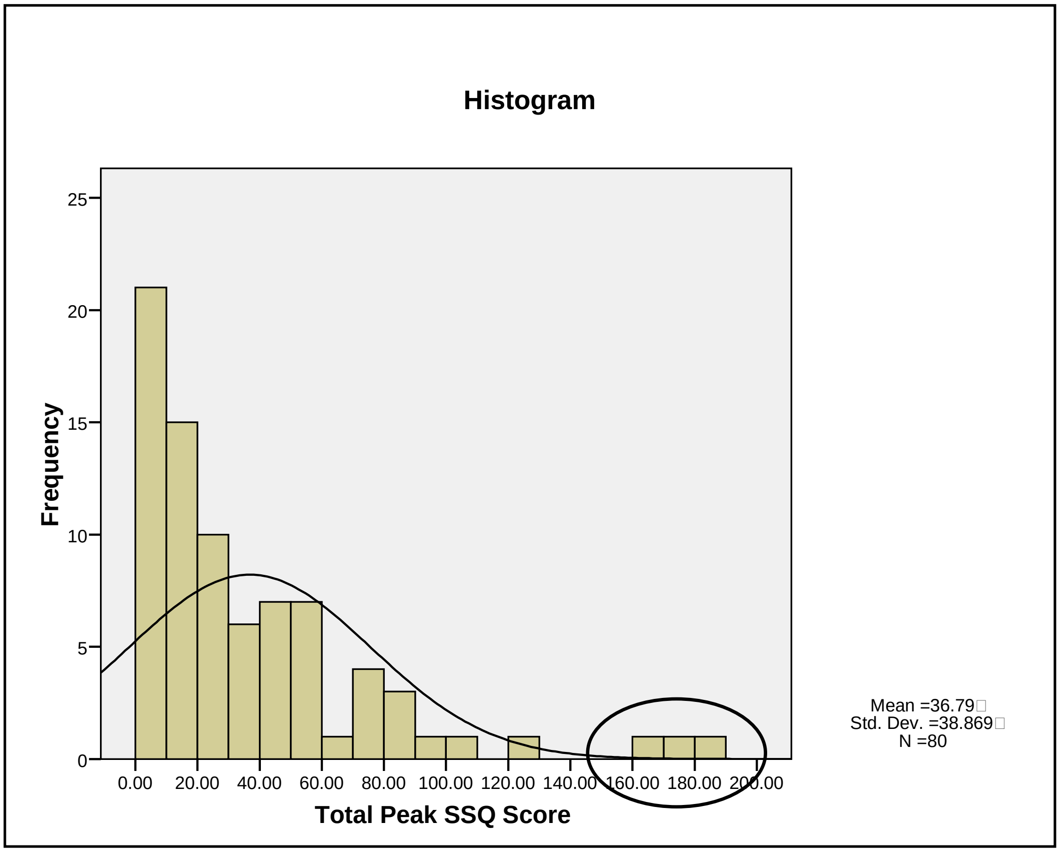

Figure 4.1. Frequency distribution of peak SSQ scores obtained in the current study. The three scores circled in the tail were identified as extreme values.

To address the problems of normality and the heterogeneity of variance, two types of data transformations were examined (Neter, Wasserman, & Kutner, 1990, pp. 142-148). First, a natural log transformation of peak SSQ scores was performed. The natural log transformation did not adequately correct the normality of the distribution. Second, a square root transformation of peak SSQ scores was performed. The square root transformation corrected the normality and the heterogeneity of variance problems. See Figure 4.2 showing a histogram of the square root transformation of peak SSQ scores.

Following the square root transformation, the condition with the greatest amount of variance (condition 4) and the condition with the least amount of variance (condition 2) differed by a factor slightly above 5. See Appendix H for histograms of the square root transformations of peak SSQ scores for each condition. In order to address the third problem and the influence of the extreme values, statistical analyses of the hypotheses related to SS were performed with and without the data obtained from the three participants who obtained the extreme values mentioned above. All statistical analyses of the hypotheses related to SS used the square root transformation of peak SSQ scores.

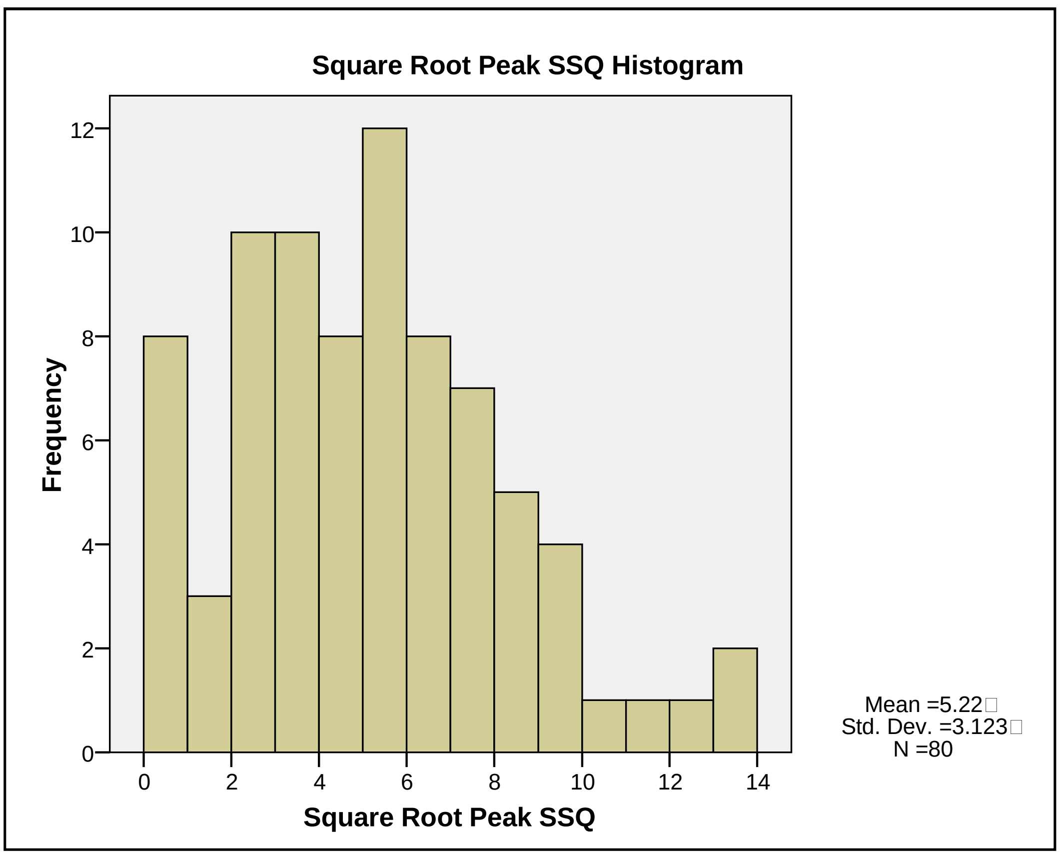

Figure 4.2. Frequency distribution of the square root transformation of peak SSQ scores obtained in the current study.

Hypothesized Results

Simulator Sickness with Extreme Values

The cell sizes, means, and standard deviations for the 2X2X2 factorial design are presented in Table 4.1. The three-way between-subjects analysis of variance yielded a main effect of peripheral vision, $F(1,72) = 6.90$, $p = .01$, indicating peak SSQ scores were significantly higher when peripheral vision was occluded ($M = 6.11$, $SD = 3.22$) than when peripheral vision was included ($M = 4.32$, $SD = 2.79$;. see Figure 4.3). The main effect of update delay was not statistically significant, $F(1,72) = 1.97$, $p = .17$, indicating peak SSQ scores with an additional update delay of ~200 ms ($M = 5.69$, $SD = 3.09$) were not different than with no additional update delay ($M = 4.74$, $SD = 3.13$; see Figure 4.4). The main effect of image scale factor was not statistically significant, $F(1,72) = .143$, $p = .71$, indicating peak SSQ scores with an image scale factor of 2 ($M = 5.34$, $SD = 2.73$) were not different than with an image scale factor of .88 ($M = 5.09$, $SD = 3.51$; see Figure 4.5). A significant update delay X peripheral vision interaction effect was not revealed, $F(1,72) = .45$, $p = .51$, indicating that update delay effect was not dependent on peripheral vision (see Figure 4.6). No other significant or marginally significant effects were revealed.

Table 4.1. Means and standard deviations (SD) of the square root of peak SSQ score as function of factor.

Update Delay	Image Scale Factor	Peripheral Vision	Mean	SD	N
0 ms	2	Inclusion	4.44	3.54	10
		Occlusion	5.03	1.85	10
		Total	4.74	2.77	20
	.88	Inclusion	3.71	2.44	10
		Occlusion	5.77	4.22	10
		Total	4.74	3.52	20
	Total	Inclusion	4.44	2.98	20
		Occlusion	5.40	3.19	20
		Total	4.74	3.13	40
200 ms	2	Inclusion	5.36	2.44	10
		Occlusion	6.54	2.77	10
		Total	5.95	2.61	20
	.88	Inclusion	3.79	2.71	10
		Occlusion	7.08	3.64	10
		Total	5.44	3.55	20
	Total	Inclusion	4.57	2.63	20
		Occlusion	6.81	3.16	20
		Total	5.69	3.09	40
Total	2	Inclusion	4.90	3.00	20
		Occlusion	5.79	2.42	20
		Total	5.34	2.73	40
	.88	Inclusion	3.75	2.51	20
		Occlusion	6.43	3.89	20
		Total	5.09	3.51	40
	Total	Inclusion	4.32	2.79	40
		Occlusion	6.11	3.22	40
		Total	5.22	3.12	80

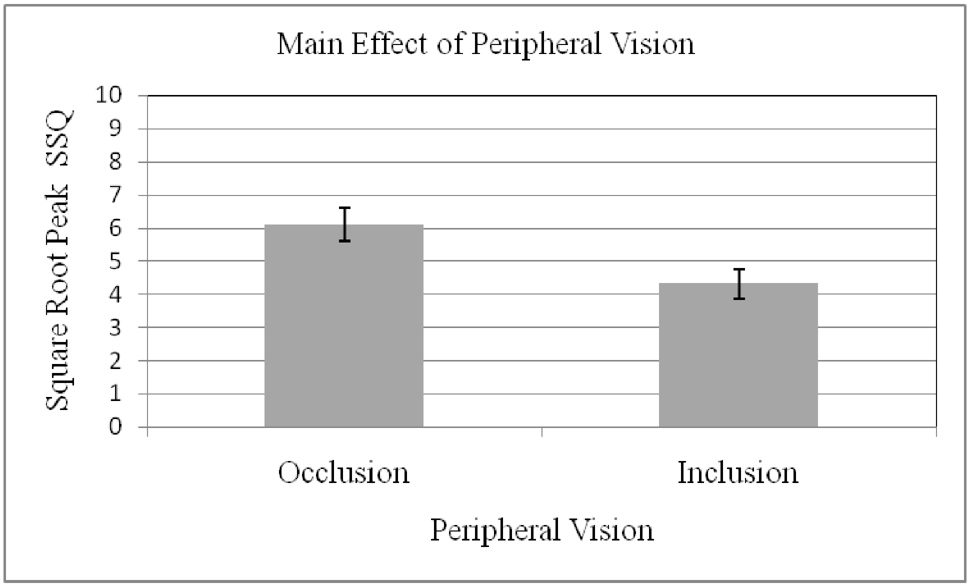

Figure 4.3. Significant main effect of peripheral vision with standard error bars.

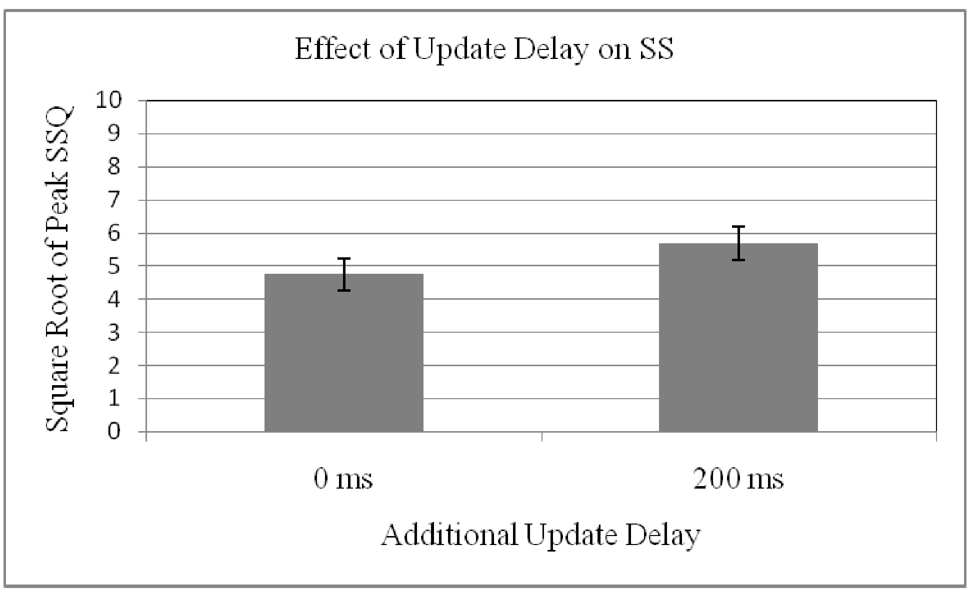

Figure 4.4. Effect of update delay with standard error bars.

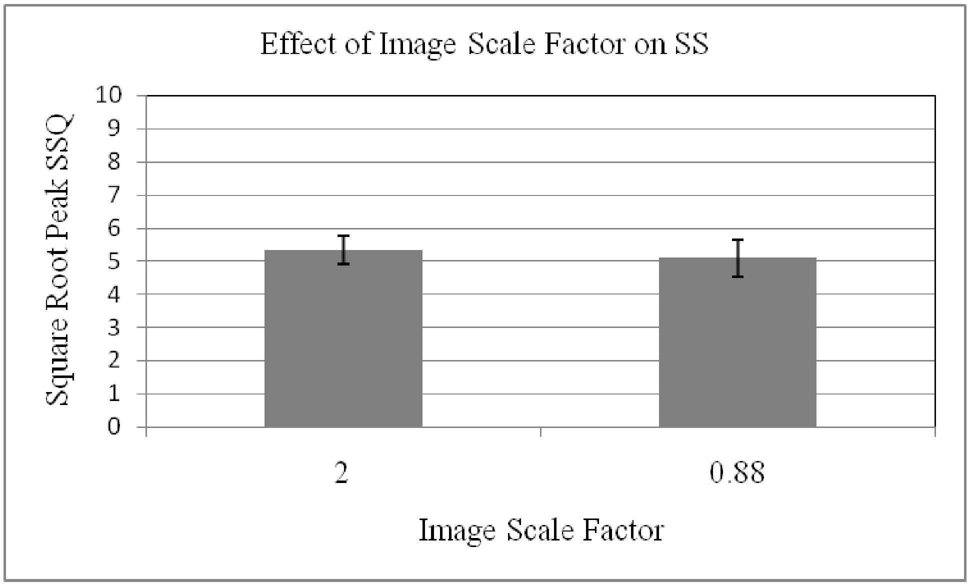

Figure 4.5. Effect of image scale factor with standard error bars.

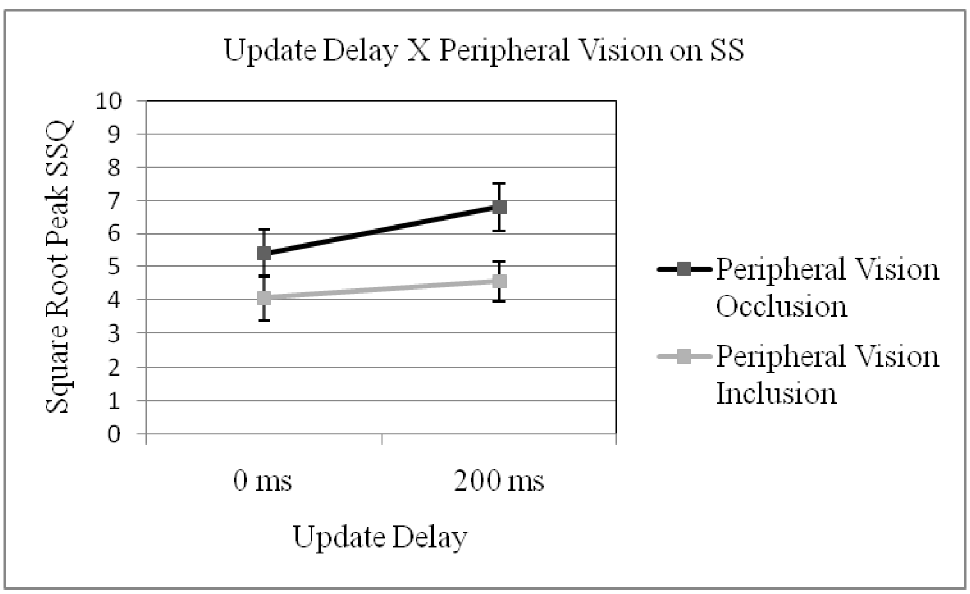

Figure 4.6. Update delay X peripheral vision effect with standard error bars.

Simulator Sickness without Extreme Values

The cell sizes, means, and standard deviations for the 2X2X2 factorial design without the three extreme values are presented in Table 4.2. The three-way between-subjects analysis of variance yielded a main effect of update delay, $F(1,69) = 4.05$, $p = .048$, indicating peak SSQ scores were significantly higher with an additional update delay of ~200 ms ($M = 5.49$, $SD = 2.85$) than with no additional update delay ($M = 4.31$, $SD = 2.54$;. see Figure 4.7). The main effect of peripheral vision was marginally significant, $F(1,69) = 3.61$, $p = .06$, indicating peak SSQ scores were higher when peripheral vision was occluded ($M = 5.54$, $SD = 2.85$) than when peripheral vision was included ($M = 4.32$, $SD = 2.79$; see Figure 4.8). The main effect of image scale factor was not statistically significant, $F(1,69) = 2.12$, $p = .15$, indicating peak SSQ scores with an image scale factor of 2 ($M = 5.34$, $SD = 2.73$) were not different than with an image scale factor of .88 ($M = 4.43$, $SD = 2.73$; see Figure 4.9). A significant update delay X peripheral vision interaction effect was not revealed, $F(1,69) = 1.42$, $p = .24$, indicating that update delay effect was not dependent on peripheral vision (see Figure 4.10). No other significant or marginally significant effects were revealed.

Table 4.2. Means and standard deviations (SD) of the square root of peak SSQ score as function of factor without extreme values.

Update Delay	Image Scale Factor	Peripheral Vision	Mean	SD	N
0 ms	2	Inclusion	4.44	3.54	10
		Occlusion	5.03	1.85	10
		Total	4.74	2.77	20
	.88	Inclusion	3.71	2.44	10
		Occlusion	3.97	2.10	8
		Total	3.82	2.23	18
	Total	Inclusion	4.07	2.98	20
		Occlusion	4.56	1.98	18
		Total	4.31	2.54	38
200 ms	2	Inclusion	5.36	2.44	10
		Occlusion	6.54	2.77	10
		Total	5.95	2.61	20
	.88	Inclusion	3.79	2.71	10
		Occlusion	6.37	3.02	9
		Total	5.01	3.08	19
	Total	Inclusion	4.57	2.63	20
		Occlusion	6.46	2.81	19
		Total	5.49	2.85	39
Total	2	Inclusion	4.90	3.00	20
		Occlusion	5.79	2.42	20
		Total	5.34	2.73	40
	.88	Inclusion	3.75	2.51	20
		Occlusion	5.24	2.83	17
		Total	4.43	2.73	37
	Total	Inclusion	4.32	2.79	40
		Occlusion	5.54	2.59	37
		Total	4.91	2.75	77

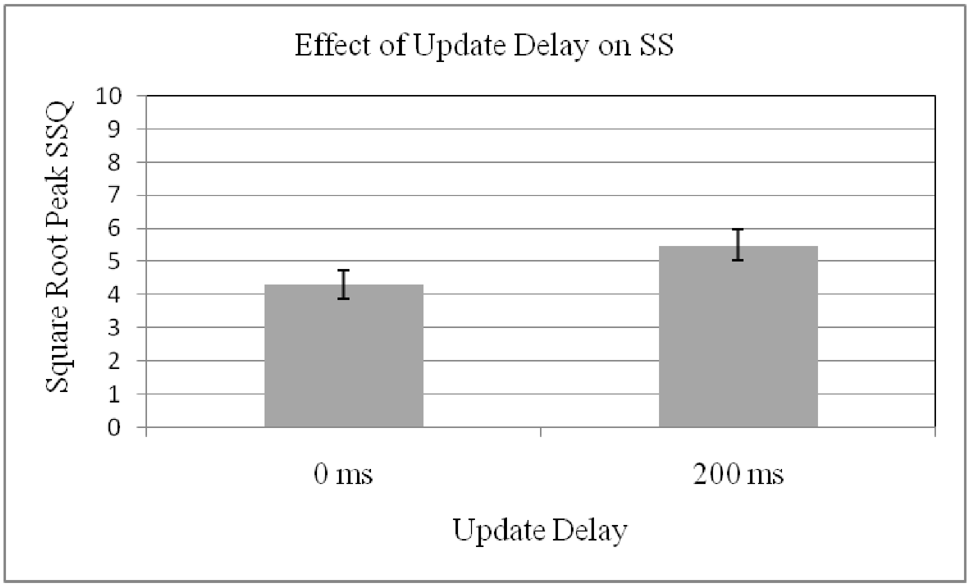

Figure 4.7. Significant main effect of update delay with standard error bars.

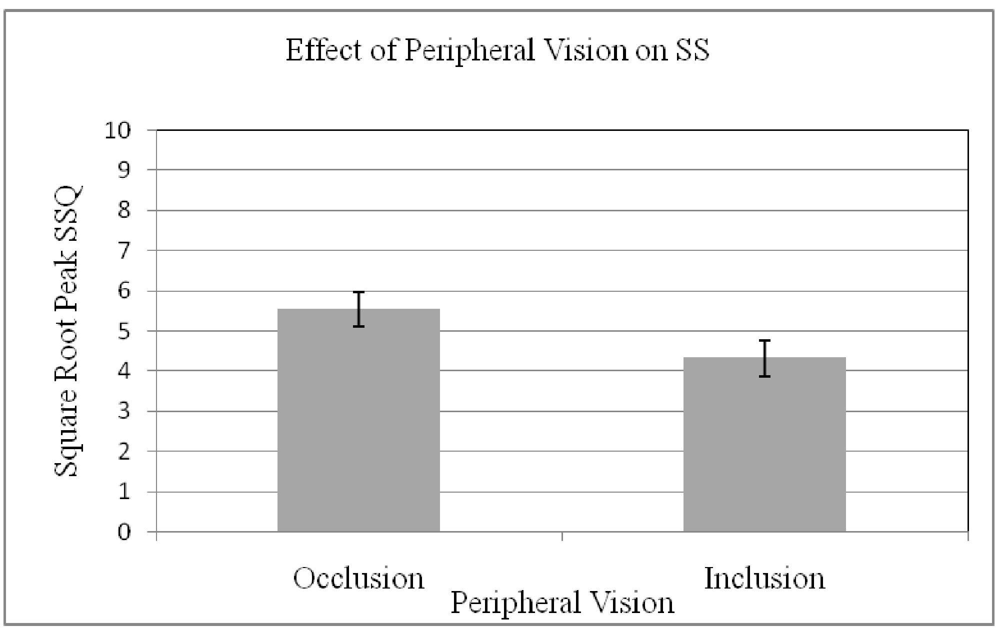

Figure 4.8. Marginally significant main effect of peripheral vision with standard error bars.

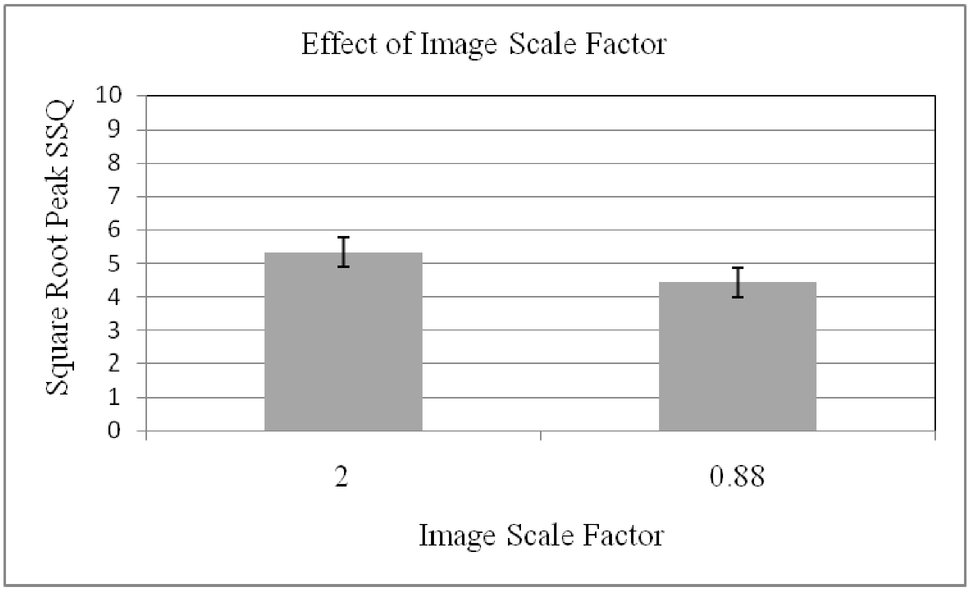

Figure 4.9. Effect of image scale factor with standard error bars.

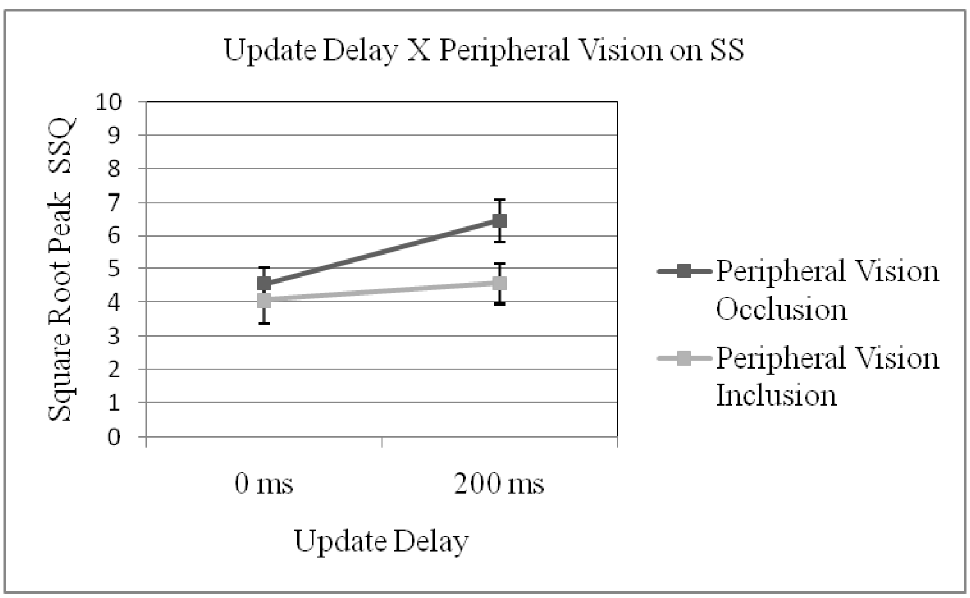

Figure 4.10. Update delay X peripheral vision effect with standard error bars.

Presence

Total PQ scores were obtained from only 79 participants. One participant failed to complete the entire PQ. The cell sizes, means, and standard deviations for the 2X2X2 factorial design are presented in Table 4.3. PQ scores met the assumptions of normality and homogeneity of variance. See Figure 4.11 showing a histogram of PQ scores. The three-way between-subjects analysis of variance did not yield any significant or marginally significant main effects or interaction effects of update delay, image scale factor, or peripheral vision on presence. The main effect of update delay was not statistically significant, $F(1,71) = .26$, $p = .61$. The main effect of image scale factor was not statistically significant, $F(1,71) = .001$, $p = .98$. The main effect of peripheral vision was also not statistically significant, $F(1,71) = .005$, $p = .95$. See Figure 4.12 showing the overall effects on presence.

Table 4.3. Means and standard deviations (SD) of PQ score as function of factor.

Update delay	Image Scale Factor	Peripheral Vision	Mean	SD	N
0 ms	2	Inclusion	72.20	10.13	10
		Occlusion	65.60	11.91	10
		Total	68.90	11.28	20
	.88	Inclusion	69.10	12.51	10
		Occlusion	68.30	12.25	10
		Total	68.70	12.06	20
	Total	Inclusion	70.65	11.19	20
		Occlusion	66.95	11.84	20
		Total	68.80	11.53	40
200 ms	2	Inclusion	65.44	12.32	9
		Occlusion	69.00	11.56	10
		Total	67.32	11.73	19
	.88	Inclusion	66.00	14.38	10
		Occlusion	69.10	12.83	10
		Total	67.55	13.36	20
	Total	Inclusion	65.74	13.07	19
		Occlusion	69.05	11.88	20
		Total	67.44	12.42	39
Total	2	Inclusion	69.00	11.44	19
		Occlusion	67.30	11.55	20
		Total	68.13	11.38	39
	.88	Inclusion	67.55	13.21	20
		Occlusion	68.70	12.21	20
		Total	68.13	12.57	40
	Total	Inclusion	68.26	12.24	39
		Occlusion	68.00	11.76	40
		Total	68.13	11.92	79

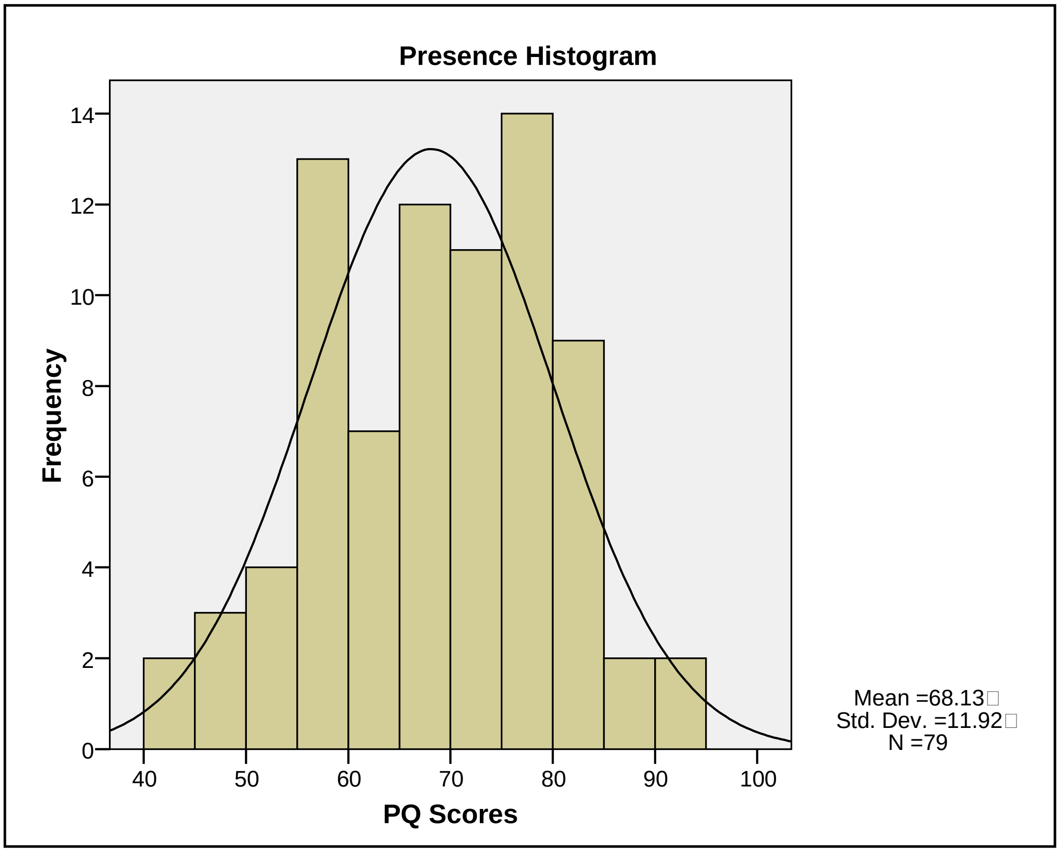

Figure 4.11. Frequency distribution of PQ scores.

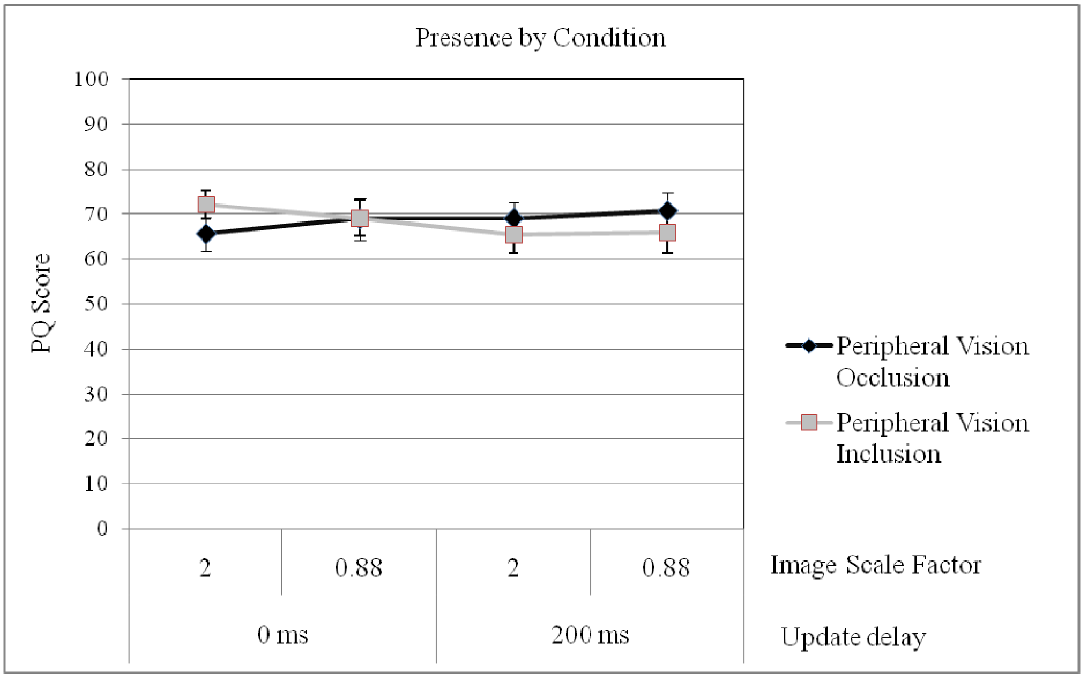

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Figure 4.12. Overall condition effects on presence.

Exploratory Results

Simulator Sickness

There was a statistically significant negative correlation of peak SSQ scores (*M* = 37.12, *SD* = 39.04, *N* = 79) and PQ scores (*M* = 68.13, *SD* = 11.92), *r(77)* = -.28, *p*= .013.

As discussed in a preceding section, participants were split into ‘sick’ and ‘not sick’ groups based upon a median split of peak SSQ scores. In all, 41 participants were placed into the ‘sick’ group and 39 participants were placed into the ‘not-sick’ group.

The relationship between update delay and sickness level was significant, χ^2 (1, *N* = 80) = 4.05, *p*= .04. See Table 4.4. Participants were more likely to be in the ‘sick’ group when subjected to the additional update delay of ~200 ms than those who were subjected to 0 ms of additional update delay.

Table 4.4. Update Delay * Sickness Crosstabulation

			Sickness		Total
			Not Sick	Sick	Not Sick
Update Delay	0 ms	Count	24	16	40
		Expected Count	19.5	20.5	40.0
		% within Update Delay	60.0%	40.0%	100.0%
		% within Sickness	61.5%	39.0%	50.0%
	200 ms	Count	15	25	40
		Expected Count	19.5	20.5	40.0
		% within Update Delay	37.5%	62.5%	100.0%
		% within Sickness	38.5%	61.0%	50.0%
Total		Count	39	41	80
		Expected Count	39.0	41.0	80.0
		% within Update Delay	48.8%	51.3%	100.0%
		% within Sickness	100.0%	100.0%	100.0%

The relationship between image scale factor and sickness level was not statistically significant, χ^2 (1, N = 80) = .45, p= .50. See Table 4.5. Participants were not more or less likely to be in the ‘sick’ or ‘not sick’ group when subjected to an image scale factor of 2 or .88.

Table 4.5. Image Scale Factor * Sickness Level Crosstabulation

			Sickness Level		Total
			Not Sick	Sick	Not Sick
Image Scale Factor	2	Count	18	22	40
		Expected Count	19.5	20.5	40.0
		% within Image Scale Factor	45.0%	55.0%	100.0%
		% within Sickness Level	46.2%	53.7%	50.0%
	.88	Count	21	19	40
		Expected Count	19.5	20.5	40.0
		% within Image Scale Factor	52.5%	47.5%	100.0%
		% within Sickness Level	53.8%	46.3%	50.0%
Total		Count	39	41	80
		Expected Count	39.0	41.0	80.0
		% within Image Scale Factor	48.8%	51.3%	100.0%
		% within Sickness Level	100.0%	100.0%	100.0%

A trend in the relationship between peripheral vision and sickness level was revealed, $\square^2$ (1, N = 80) = 2.45, p= .12. See Table 4.6. Participants tended to be more likely to be in the 'sick' group with peripheral vision occlusion than participants with peripheral vision inclusion, albeit not statistically significant.

Table 4.6. Peripheral Vision * Sickness Level Crosstabulation

			Sickness Level		Total
			Not Sick	Sick	Not Sick
Peripheral Vision	Inclusion	Count	23	17	40
		Expected Count	19.5	20.5	40.0
		% within Peripheral Vision	57.5%	42.5%	100.0%
		% within Sickness Level	59.0%	41.5%	50.0%
	Occlusion	Count	16	24	40
		Expected Count	19.5	20.5	40.0
		% within Peripheral Vision	40.0%	60.0%	100.0%
		% within Sickness Level	41.0%	58.5%	50.0%
Total		Count	39	41	80
		Expected Count	39.0	41.0	80.0
		% within Peripheral Vision	48.8%	51.3%	100.0%
		% within Sickness Level	100.0%	100.0%	100.0%

Effect of Trial

The effect of trial (i.e. time) was investigated by examining participants' SSQ scores at every time of SSQ administration. Only SSQ scores obtained from those who completed all experimental trials (i.e. did not withdraw) were used for analysis (N = 73). See Table 4.7 showing the cell sizes, means, and standard deviations of the repeated measures design.

Table 4.7. Means and standard deviations (SD) of total SSQ score as function of trial.

SSQ/Trial	Mean	SD	N
Pre Practice SSQ	1.79	5.11	73
Post Practice SSQ	7.38	12.48	73
Trial 1	9.79	16.21	73
Trial 2	13.88	21.23	73
Trial 3	18.85	25.38	73
Trial 4	24.49	33.41	73
Trial 5	32.33	37.16	73
Post 5 min	10.30	18.23	73
Post 10 min	5.12	11.93	73

A repeated measures analysis of variance was employed to investigate the effect of trial. Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(35) = 596.67$, $p < .05$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .24$). The results revealed a significant effect of trial on SSQ scores, $F(1.88, 135.09) = 36.32$, $p < .01$. SSQ scores increased as trials increased and returned to pre-experimental trial levels during post exposure. See Figure 4.13 showing the effect of trial on total SSQ score.

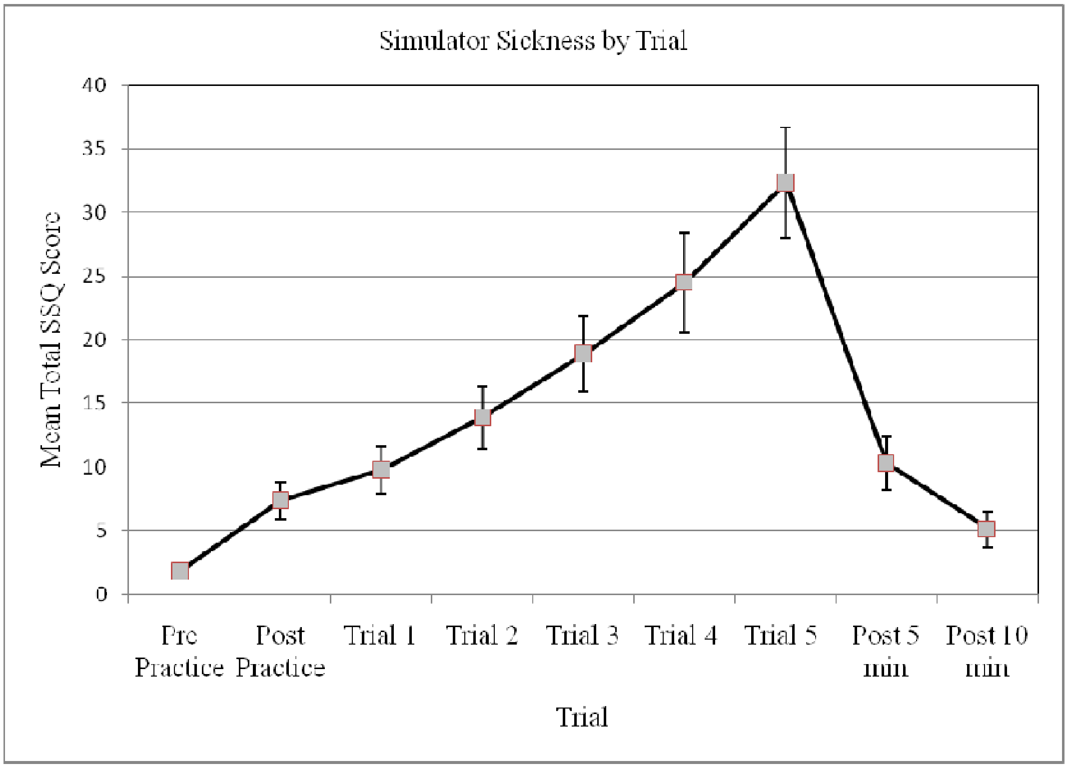

Figure 4.13. Effect of trial on simulator sickness as measured by mean total SSQ score with standard error bars. Mean SSQ scores are listed. Effect of trial was significant, $F(1.88, 135.09) = 36.32$, $p < .01$. Significant pairwise differences were revealed between: pre-practice and all except post 10 min; post-practice and trials 3-5; trial 1 and 2-5; trial 2 and 3-5; trial 2 and post 10 min; trial 3 and 4-5; trial 3 and post 5 min; trial 3 and post 10 min; trial 4 and 5; trial 4 and post 5 min; trial 4 and post 10 min; trial 5 and all; and post 5 min and post 10 min. All pairwise differences were significant at $p \leq .01$.

Post hoc Bonferroni pairwise comparisons revealed significant differences between all trials (i.e. SSQ administrations) except between pre practice and 10 min post exposure, post practice and trial 1, post practice and trial 2, post practice and 5 min post exposure, post practice and 10 min post exposure, trial 1 and 5 min post exposure, trial 1 and 10 min post exposure, and trial 2 and 5 min post exposure. To summarize, pre practice SSQ score was significantly less than all other SSQ scores except at 10 min post exposure. Trial 5 SSQ (i.e. last experimental trial) score was significantly higher than all other SSQ scores. Post exposure SSQ scores (post 5 min and 10 min) were significantly less than all other SSQ scores except pre practice, post practice, trial 1, and trial 2. SSQ scores increased as trial, or time increased and returned to pre-experimental trial levels once the experimental session ended and the HMD was removed.

Participant Withdrawal

Participant withdrawal was operationally defined as those participants who terminated participation before completion of all 5 experimental trials. The chi-square analysis included all 80 participants. Recall the use of the hand-rail was nested in the experimental design in a manner to have 40 participants who grasped the hand-rail and 40 participants who did not grasp the hand-rail. Seven out of 80 participants withdrew from the experiment.

A 2X2 chi-square test of independence revealed a significant relationship between the use of the hand-rail and participant withdrawal, χ^2 (1, *N* = 80) = 7.67, $p < .01$. See Table 4.8. However, the χ^2 expected cell count assumption was violated. Two cells (50%) had expected counts less than five. To compensate for this violation, the Fisher's exact test was employed. Participants who did not grasp the hand-rail were significantly more likely to withdraw than those who grasped the hand-rail (1, *N* = 80, $p = .012$, two-tailed Fisher's exact test).

Table 4.8. Handrail * Participant Withdrawal Crosstabulation

			Participant Withdrawal		Total
			no	yes	no
Handrail	Did Not Grasp	Count	33	7	40
		Expected Count	36.5	3.5	40.0
		% within Handrail	82.5%	17.5%	100.0%
		% within Participant Withdrawal	45.2%	100.0%	50.0%
	Grasped	Count	40	0	40
		Expected Count	36.5	3.5	40.0
		% within Handrail	100.0%	.0%	100.0%
		% within Participant Withdrawal	54.8%	.0%	50.0%
Total		Count	73	7	80
		Expected Count	73.0	7.0	80.0
		% within Handrail	91.3%	8.8%	100.0%
		% within Participant Withdrawal	100.0%	100.0%	100.0%

Head Movements

Upon completion of designing the current study, there was a concern for potential systematic condition effects related to head movements. To address this concern, head movement velocities were obtained from 79 participants. Due to experimenter error in collecting head movement data, one participant was not included. The cell sizes, means, and standard deviations for the 2X2X2 factorial design are presented in Table 4.9.

Table 4.9. Means and standard deviations (SD) of head movement velocity (deg/sec) as function of factor.

Update Delay	Image Scale Factor	Peripheral Vision	Mean (°/s)	SD (°/s)	N
0 ms	2	Inclusion	27.34	4.19	10
		Occlusion	28.64	3.99	10
		Total	27.99	4.04	20
	.88	Inclusion	28.55	4.71	9
		Occlusion	24.48	3.34	10
		Total	26.41	4.45	19
	Total	Inclusion	27.91	4.36	19
		Occlusion	26.56	4.17	20
		Total	27.22	4.27	39
200 ms	2	Inclusion	26.65	4.25	10
		Occlusion	30.55	4.92	10
		Total	28.60	4.90	20
	.88	Inclusion	26.66	3.95	10
		Occlusion	27.36	27.34	10
		Total	27.01	3.29	20
	Total	Inclusion	26.66	3.99	20
		Occlusion	28.96	4.18	20
		Total	27.81	4.20	40
Total	2	Inclusion	26.99	4.12	20
		Occlusion	29.59	4.47	20
		Total	28.29	4.44	40
	.88	Inclusion	27.56	4.32	19
		Occlusion	25.92	3.28	20
		Total	26.72	3.86	39
	Total	Inclusion	27.27	4.17	39
		Occlusion	27.76	4.30	40
		Total	27.52	4.21	79

The three-way between-subjects analysis of variance yielded no significant main effects of update delay, $F(1,71) = .38$, $p > .05$, or peripheral vision, $F(1,71) = .25$, $p > .05$, indicating no significant differences in head movement velocity between update delay or peripheral vision. A marginally significant main effect of image scale factor was revealed, *F*(1,71) = 2.82, *p*= .097, indicating head movement velocity was greater with an image scale factor of 2 (*M* = 28.29, *SD* = 4.44) than with an image scale factor of .88 (*M* = 26.72, *SD* = 3.86; see Figure 4.14). A significant update delay X peripheral vision interaction effect was revealed, *F*(1,71) = 4.10, *p*= .047, indicating that update delay effect was dependent on level of peripheral vision (see Figure 4.15). A significant image scale factor X peripheral vision interaction effect was also revealed, *F*(1,71) = 5.54, *p*= .02, indicating that image scale factor effect was dependent on level of peripheral vision (see Figure 4.16). No other significant or marginally significant effects were revealed.

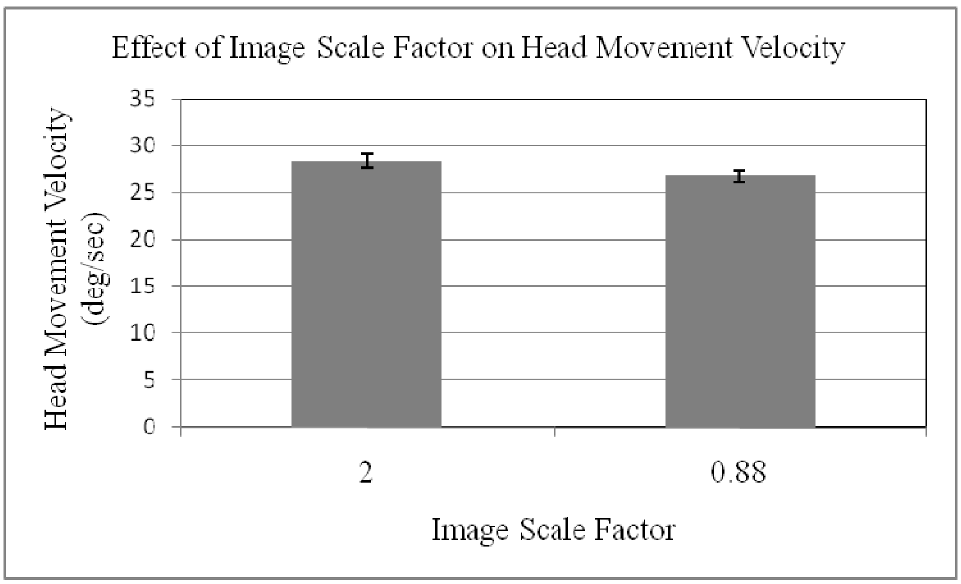

Figure 4.14. Marginally significant effect of image scale factor with standard error bars.

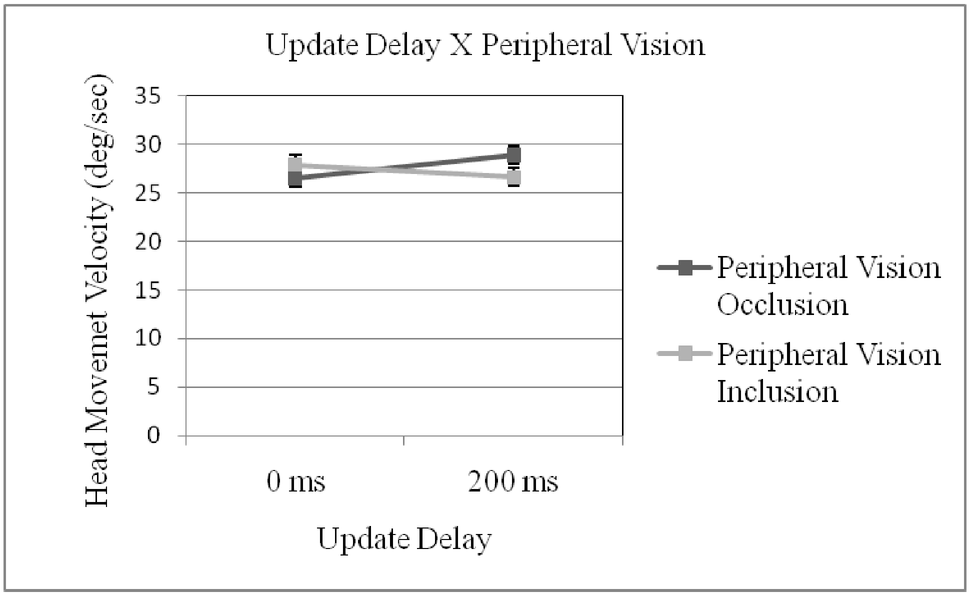

Figure 4.15. Significant update delay X peripheral vision interaction effect with standard error bars.

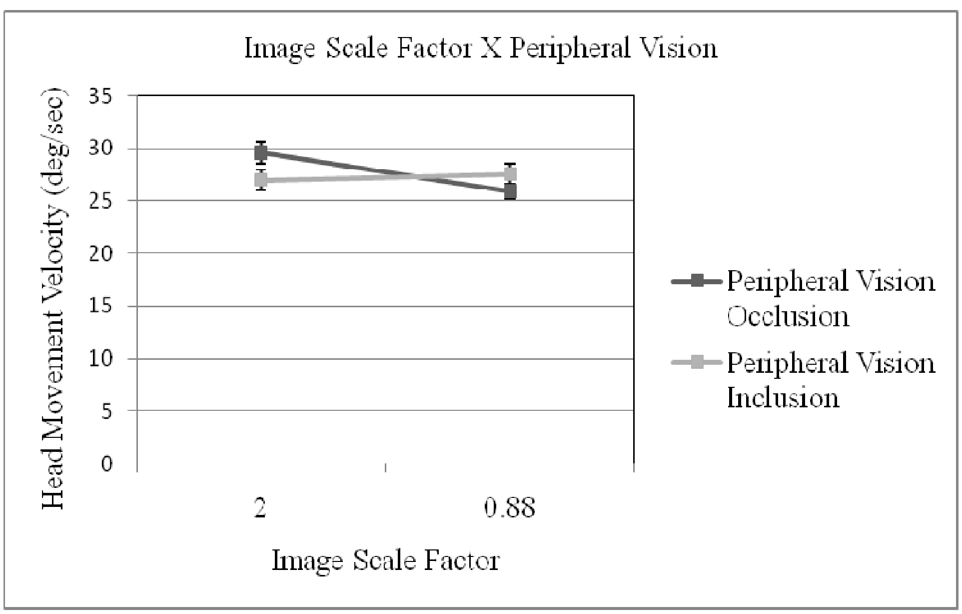

Figure 4.16. Significant image scale factor X peripheral vision interaction effect with standard error bars.

To further examine any potential systematic errors relating to head movements in the current study, the Pearson's bivariate correlation was performed to investigate the relationship between head movement velocity and peak SSQ scores. The correlation of peak SSQ scores (M = 37.16, SD = 38.97, N = 79) and head movement velocity (M = 27.52°/s, SD = 4.21°/s) was not statistically significant, $r(77)$ = -.13, p= .25.

CHAPTER V

DISCUSSION

The goal of the current work was to investigate the question, “What characteristics of HMDs make people sick?” More specifically, the effects of update delay, image scale factor, and peripheral vision were examined on SS and presence. A secondary goal of the current study was to examine the relationship between SS and presence. Participants in the current study made active head movements and performed a simple visual search task while donning an HMD that displayed a real image of the laboratory. It was hypothesized that update delay and image scale factor would have a significant main effect on SS. In addition, a significant update delay X peripheral vision interaction effect was hypothesized. Regarding presence, significant main effects of update delay, image scale factor, and peripheral vision were hypothesized. Head movement velocity measurements were collected to investigate any potential systematic errors between conditions relating to head movements.

Hypothesized Results

Simulator Sickness

The analyses with and without those peak SSQ scores that were identified as extreme values revealed a set of two different results with a common effect of peripheral vision and image scale factor. The hypothesized main effect of image scale factor on SS was not supported in either analysis. There was no difference in SS between those participants who were exposed to an image scale factor of 2 and those who were exposed to an image scale factor of .88. SS was not significantly different with a GFOV of 20° as compared to a GFOV of 45° when physical FOV of 40° was held constant. In addition, the hypothesized update delay X peripheral vision interaction effect on SS was not supported in either analysis. SS was not greater when participants were exposed to an additional update delay of ~200 ms when peripheral vision was occluded. Another common effect involved peripheral vision. When the analysis included peak SSQ scores from all participants, including those who obtained extreme values, a significant main effect of peripheral vision on SS was revealed, although not hypothesized. When the extreme values were removed, the main effect of peripheral vision on SS was revealed to be marginally significant.

The extreme values appeared to have had the greatest influence on the effect of update delay. A significant main effect of update delay on SS was revealed when the extreme values were not included in the analysis. However, the main effect of update delay on SS was not statistically significant when the extreme values were included in the analysis. In both analyses, SS was greater when participants were exposed to an additional ~200 ms of update delay than those who were exposed to the inherent update delay of the system (no additional update delay). The chi-square analysis of SS groups (‘sick’ and ‘not-sick’) supported the update delay effect, which will be fully discussed below.

To summarize, not including the extreme values enhanced the effect of update delay and lessened the effect of peripheral vision. Solely based on the results of the ANOVAs (with and without extreme values), it is not clear whether the hypothesized main effect of update delay on SS was or was not supported. However, it is apparent that the hypothesized main effect of image scale factor on SS and the update delay X peripheral vision interaction effect on SS were not supported since both analyses yielded similar results. It is also evident that peripheral vision occlusion elicited greater SS than peripheral vision inclusion since the effect of peripheral vision was similar in both analyses.

Although there has been inconsistent empirical findings regarding the causal relationship between update delay and SS (DiZio & Lackner, 1997; Draper et al., 2001), it is widely accepted that update delay elicits SS. This widely accepted relationship is often explained by Reason and Brand’s (1975) sensory conflict theory of MS. Update delay brings forth conflicting visual and vestibular information regarding motion. More specifically, when appreciable update delays are present in a HMD VE, there are epochs in which the visual system senses motion and the vestibular system does not, as well as in the converse.

The findings of the current study regarding update delay are consistent with both the findings of DiZio and Lackner (1997), and the findings of Draper et al., (2001). Regarding image scale factor, the results of the current study are inconsistent to both DiZio and Lackner (1997) and Draper et al. (2001). DiZio and Lackner (1997) suggested SS to increase as update delay increased, but to decrease when FOV was reduced in half. Draper et al. (2001) did not reveal an effect of update delay on SS but did reveal an effect of image scale factor on SS. The research of DiZio and Lackner (1997) and Draper et al. (2001) are most similar to the current study and will be compared further.

Two primary differences existed between the methodology of the current study and the abovementioned studies (DiZio & Lackner, 1997; Draper et al., 2001). Both studies used a within-subjects design with a smaller sample size than the current study. DiZio and Lackner (1997) examined update delay ranging from 67 ms to 367 ms and revealed SS to increase as a function of increasing update delay. This is consistent with the findings of the current study when the extreme values were not included in that an additional update delay elicited greater SS. The current study did not examine a range of update delays. However, Draper et al. (2001) did not reveal a difference in SS between update delays of 173 ms and 298 ms. This is inconsistent with the findings of DiZio and Lackner (1997) and with the findings of the current study when the extreme values were not included. One possible explanation for the discrepancy in Draper et al. (2001) may be one of power. Draper et al.'s (2001) sample size consisted of only 10 participants. Another possible explanation may simply be that the critical amount of update delay to elicit SS was around 173 ms and therefore the greater update delay did not cause an appreciable effect. DiZio and Lackner (1997) demonstrated SS to increase as update delay increased but did not discussed differences in SS between pairs of update delays. Although the inherent system update delay in the current study is not known, the no additional update delay may have been below such a critical point, if one exists, to have caused a significant difference in SS.

However, if the extreme values did reflect the behavior in the population, the findings of the current study are inconsistent with DiZio and Lackner (1997) and consistent with Draper et al. (2001). The current study and Draper et al. (2001) used the

SSQ as the measure of SS. DiZio and Lackner (1997) used a different measure, the Graybiel categorization system (Graybiel, Wood, Miller, & Cramer, 1968, as cited in DiZio & Lackner, 1997). In addition, similar to the above, DiZio and Lackner (1997) did not report differences in SS between pairs of update delays. It is possible that the effect revealed in DiZio and Lackner (1997) was between update delays with a greater difference than ~200 ms as in the current study.

The current study failed to demonstrate an effect of image scale factor on SS whereas Draper et al. (2001) and DiZio and Lackner (1997) revealed effects of image scale factor and FOV, respectively, on SS. The main difficulty in comparing the effect found in DiZio and Lackner (1997) with the current study, as well as with Draper et al. (2001), is that it is not known what the image scale factor was in DiZio and Lackner (1997). As discussed in Draper et al. (2001) and previously in this dissertation, most of the previous research does not address the discrepancy in GFOV and physical FOV and the resulting image scale factor, but rather just physical FOV or GFOV. All that was reported in DiZio and Lackner (1997) was that when the full FOV (126° horizontal X 74° vertical) was reduced in half (63° horizontal X 37° vertical) with an update delay of 267 ms, SS severity was reduced in half. Additionally, this effect was only examined with an update delay of 267 ms. Draper et al. (2001) examined an image scale factor of .5, 1, and 2 on SS and revealed SS to be significantly greater with an image scale factor of .5 and 2 as compared to an image scale factor of unity, or 1. The image scale factors examined in the current study (i.e. 2 and .88) are similar to those in Draper et al. (2001). Unlike Draper et al. (2001), image scale factor did not have an effect on SS. The current researcher is not aware of an apparent explanation for these inconsistent findings between the current study and the aforesaid research (DiZio & Lackner, 1997; Draper et al., 2001) other than the previously described differences in methodology. More specifically, the current study was a between-subjects design and it is unclear as to if physical FOV or GFOV was manipulated in DiZio and Lackner (1997). If physical FOV was indeed manipulated in DiZio and Lackner (1997), it is possible that more peripheral vision was available when FOV was reduced in half as compared to full FOV, reducing SS as was demonstrated in the current study.

Although not hypothesized, participants did report greater SS when peripheral vision was occluded by the use of the ‘eye-cups’ as compared to peripheral vision inclusion (no ‘eye-cups’). This effect was evident in both analyses of with and without extreme values. Peripheral vision occlusion may enhance the sensory conflict previously discussed between the visual and vestibular systems brought forth by update delay. When peripheral vision is occluded, the individual is a ‘slave’ to the consequences of the display. Visual information regarding motion is solely provided by the display since external visual stimuli from the real-world are occluded. When peripheral vision is included, the individual is more likely to receive congruent visual and vestibular information regarding motion, lessening the sensory conflict between these two systems. Although visual information provided by the HMD display is incongruent with vestibular information, due to update delay, visual information from the real-world provided in the periphery is congruent to vestibular information. Even though an update delay X peripheral vision interaction effect was not revealed, peripheral vision occlusion may have enhanced the perceptibility and effect of update delay in both levels of update delay. Also, when peripheral vision is occluded, the user does not receive optic flow information in the periphery when making head movements. The lack of expected optic flow information in the periphery may provide another source of sensory conflict between the visual and vestibular systems. Overall, the user is subjected to all possible detrimental effects of the HMD display when peripheral vision is occluded.

Presence

An effect of update delay, image scale factor, or peripheral vision on ‘being there,’ or presence, was not observed in the current study. Participants’ experience of presence did not differ across conditions. This was an unexpected finding considering main effects of all were hypothesized.

Update delay was expected to affect presence because with an appreciable update delay there would be a lower sense of ‘being’ in a ‘place’ other than the current physical locale due to unnatural visual distortions caused by an appreciable update delay. Image scale factor was also expected to have an effect on presence because it is a common belief that more visual information (i.e. wider FOV) would lead one to be more likely to experience presence. Also, presence was expected to be greater with an image scale factor close to unity because there would be less magnification or minification distortions and hence, a more natural and realistic image (Hendrix & Barfield, 1996). In the current study, the image scale factor of .88 represented a wider GFOV and an image scale factor closer to unity than the other image scale factor of 2. Based on Slater et al. (1996) and Witmer and Singer (1998), presence was expected to be greater when peripheral vision was occluded than when it was included. According to Witmer and Singer (1998), immersion is a necessary component to achieve a sense of presence. Level of immersion is greater when there is more isolation from external, real-world stimuli (Slater et al., 1996; Witmer and Singer, 1998). Peripheral vision occlusion isolated participants in the current study from external visual stimuli in a greater degree than peripheral vision inclusion. However, none of the abovementioned hypothesized effects were observed in the current study.

There are several possible explanations for the failure to demonstrate any effects. First, in general it was difficult to make comparisons between studies investigating presence because of the inconsistency in implemented measurements of presence. Studies have used in-house questionnaires (Hendrix & Barfield, 1995), physiological measures of heart-rate (Meehan et al., 2005), and the PQ (Moss et al., 2008). To date, there is not a consistent and standard measure evaluating presence in the literature. Presence is a relatively young construct and not yet fully understood. As admitted by the authors of the PQ (Jerome et al., 2005; Witmer & Singer, 1998), the PQ is a work in progress and needs further investigation in its validity. The PQ has gone through several iterations since 1994 (Jerome et al., 2005). Further, only a limited sub-set of items were relevant and hence used, in the current study.

Second, the scene displayed by the HMD and viewed by the participants was the real-world image of the laboratory that they were physically located within, captured by a video camera. The essence of the presence construct is the subjective feeling of ‘being in’ an environment other than the current physical locale. The scene used in the current study was not of a different environment, it was the actual current environment. Therefore, regardless of variable manipulation, participants may not, nor would ever expect to feel as if in another environment or place. This may have also caused a ceiling effect to occur regarding PQ scores.

Third, the most promising hypothesis regarding the effect of update delay was based on a within-subjects study using the same paradigm as the current study (Moss et al., 2008). The PQ was used to measure the effects of an additional update delay of ~200 ms and no additional update delay on presence. Moss et al. (2008) did find presence to be significantly higher with no additional update delay. However, Moss et al. (2008) was a within-subjects design. Participants took part in both update delay conditions, which permitted a context for comparison when completing the PQ. The current study was between-subjects. Participants did not have a context for comparison. Also, within-subjects designs generally have more power since individual differences are controlled for to a greater degree.

Exploratory Results

Relationship between Simulator Sickness and Presence

Although there was no hypothesized relationship between SS and presence, the secondary goal of the current dissertation was to examine if any relationship existed. The results suggested that a significant negative relationship did exist between SS and presence. Participants felt less presence in the HMD VE as they became more simulator sick. Peak SSQ scores increased as PQ scores decreased. This is an interesting finding since presence was not affected by update delay, image scale factor, or peripheral vision.

However, this finding is in agreement with Witmer and Singer's (1998) construct of presence. According to Witmer and Singer (1998), involvement is a key component in obtaining presence. With that said, in order for one to be involved in the VE, one must direct attention to the VE. The negative relationship between SS and presence may be explained by a diminished level of involvement in the VE due to a shift in attention inwards to the experienced SS, rather than outwards to the VE itself, which has been predicted and demonstrated by Witmer and Singer (1998).

Sickness Levels

To further examine the effects of update delay, image scale factor, and peripheral vision on SS, participants were divided into 'sick' and 'not-sick' groups derived from a median split of peak SSQ scores (median = 26.18). There is little known regarding what SSQ score constitutes an individual to be simulator sick in an HMD VE. Therefore participants were split into a dichotomous grouping of SS to examine if the likelihood of experiencing SS was dependent on update delay, image scale factor, or peripheral vision.

SS was revealed to be significantly dependent on update delay with a trend of dependence on peripheral vision. Participants were not more or less likely to experience SS based on image scale factor. Twenty-five out of the 41 sick participants (60.98%) were sick when subjected to ~200 ms of additional update delay compared to 16 out of 41 sick participants (39.02%) when subjected to no additional update delay. Although not statistically significant, there was a trend for participants to be sick when peripheral vision was occluded as compared to when peripheral vision was included. Out of the 41 sick participants, 24 (58.54%) were sick when peripheral vision was occluded and 17

(41.46%) were sick when peripheral vision was included. There was no observed relationship between an image scale factor of 2 or .88 and SS group. Twenty-two out of 41 sick participants (53.65%) and 19 out of 41 sick participants (46.34%) were sick when subjected to an image scale factor of 2 and .88, respectively.

These results are consistent with the results of the 2X2X2 between-subjects analysis of variance when the extreme values were removed. A significant main effect and a marginally significant main effect was revealed for update delay and peripheral vision, respectively, on SS. Consistent with no observed relationship between image scale factor and SS group, a main effect of image scale factor was not revealed. The chi-square analyses of independence and the 2X2X2 between-subjects analysis of variance without the extreme values supported the hypothesized effect of update delay on SS. The analyses did not support the hypothesized effect of image scale factor on SS.

Effect of Trial

Simply being exposed to the HMD VE and performing the task increased SS. Participants reported more SS as time spent in the HMD VE increased. Participants reported negligible symptoms prior to donning the HMD before the set of practice trials. SS increased slightly post practice but increased steadily throughout the experimental trials, peaking at the conclusion of the last experimental trial (i.e. trial 5). SS then returned to pre experimental trial levels during post exposure (i.e. post 5 and 10 min). See Figure 4.13. Significant SS still existed 5 min after removing the HMD as compared to before the start of the practice trials. SS did not diminish fully until 10 min after the completion of the experimental session.

The findings regarding the effect of trial (i.e. time) is consistent with previous studies conducted using the same paradigm as the current study (Moss, Scisco, & Muth, in press; Moss et al., 2008). However, solely performing the head movement task over an extended period of time may have contributed to SS. Moss, Scisco, and Muth (in press) revealed peak SSQ scores to increase as time increased when performing the same head movement task as in the current study without donning the HMD. MS has also been suggested to be elicited by making torso movements (Bouyer & Watt, 1996). However, head movements in the current study were not as rapid as the torso movements performed in Bouyer and Watt (1996).

Participant Withdrawal

One of the more interesting findings of the current study was the unexpected rate of participant withdrawal before the implementation of the hand-rail. Prior studies conducted in our laboratory using the same paradigm as the current study observed only 2 participant withdrawals out of 80. This constituted a withdrawal rate of only 2.5%. In the current study, 7 out of the first 28 participants withdrew, constituting a withdrawal rate of 25%, extrapolating a possible 20 out of 80 participants to withdraw from the current study. The current researcher reexamined any potential differences between the current study and prior studies for a possible explanation. Prior studies gave participants the option to grasp onto a hand-rail as a safety precaution, which most, if not all, participants used. Because of this difference and the frequent withdrawal rate, the use of the hand-rail was implemented. Half of the participants in the current study, equally divided across conditions, grasped the hand-rail and the other half did not grasp the hand-rail. No additional participants withdrew from the current study, with or without grasping the hand-rail. A total of seven participants withdrew from the current study, all without grasping the hand-rail. Participants who did not grasp the hand-rail were significantly more likely to withdraw from the current study than those who did grasp the hand-rail, as revealed by the Fisher's exact test.

The highly unexpected rate of participant withdrawal warranted further exploration. Seven out of 80 participants in all withdrew from the current study. Four of the seven participants who withdrew experienced extreme responses never previously observed in the laboratory. These four participants experienced faint-like symptoms, increased warmth, confusion, ataxia, tunnel vision, and in two participants, a complete loss of vision. These participants required physical assistance to a seated position in a nearby recliner in which the extreme responses diminished shortly thereafter. During debriefing, these four participants reported to never had experienced a similar sensation, MS, or fainted before. Also, these participants reported that the experienced sensations came on abruptly.

It is unclear if these observations are an extreme response to SS or a separate phenomenon. A pattern of participant withdrawal consistently occurring in a particular condition was not observed. One of the participants was identified as obtaining an extreme value (i.e. peak SSQ was ≥ 150). Peak SSQ scores for these participants who withdrew were 71.06, 67.32, 164.56, 33.66, 59.84, 48.62, and 44.88. Several post-hoc analyses were performed regarding these participants and the overall use of the hand-rail relating to SS. The participants who withdrew experienced significantly greater SS (M =

69.99, *SD* = 43.71), as demonstrated by peak SSQ scores, than those participants who did not withdraw (*M* = 33.61, *SD* = 37.16), *t*(78) = 2.44, *p*= .02. However, a significant difference in SS did not exist between those participants who grasped the hand-rail (*M* = 35.44, *SD* = 42.19) and those who did not grasp the hand-rail (*M* = 38.15, *SD* = 35.73), *t*(78) = .31, *p*= .76. Although participants who withdrew experienced more SS, grasping the hand-rail did not have an effect on SS.

A review of SS and MS research found only a couple incidents in which such extreme responses were reported. In an examination of postural sway when fixating on a near and distant target during an unperturbed stance, Smart, Pagulayan, and Stoffregen (1998) observed strikingly similar extreme responses. Smart et al. (1998) were equally surprised in their observations since they did not intend to elicit MS. Participants in Smart et al. (1998) reported similar faint-like symptoms, confusion, tunnel vision, and increased warmth. Although the responses were unexpected, Smart et al. (1998) classified the observed occurrences as MS. Lestienne, Soechting, and Berthoz (1977) reported that 3 out of 30 participants fainted while subjected to linear vection. However, a specific explanation as to why these participants fainted was not addressed. Bouyer and Watt (1996, p. 370) reported a participant to have “mental confusion” when performing vigorous torso movements. Ehrlich and Kolasinski (1998) investigated the differences in SS symptoms between participants who withdrew from VE studies and those participants who did not withdraw from VE studies. A difference in total SSQ scores between those who withdrew and those who did not withdraw was not revealed (Ehrlich & Kolasinski, 1998).

The extreme responses observed in the current study and those mentioned in the above studies (Lestienne, 1977; Smart et al., 1998) are similar to symptoms of vasovagal syncope. However, the abovementioned studies do not discuss the possibility of a vasovagal syncope response. Briefly stated, vasovagal syncope is an autonomic nervous system response that is caused by a failure of baroreceptors to maintain heart-rate and blood pressure when blood is pooled in your legs while standing (Bosser, Caillet, Gauchard, Marcon, & Perrin, 2006). Some symptoms of vasovagal syncope are cold sweating, increased warmth, weakness, nausea, tunnel vision, dizziness, and loss of consciousness, or fainting (Bosser et al., 2006). Bosser et al. (2006) examined the relationship between MS susceptibility and vasovagal syncope susceptibility through the investigation of MS susceptibility questionnaires and vasovagal syncope susceptibility questionnaires. A relationship between vasovagal syncope and MS susceptibility in adults was revealed (Bosser et al., 2006). The one feature in common with the abovementioned studies (Bouyer & Watt, 1996; Lestienne, 1977; Smart et al., 1998) and the current study was that participants had to stand for the experimental task. Although participants in the current study were instructed to stand in a comfortable position and not to 'lock' their knees, it is quite possible that these participants did 'lock' their knees causing blood to pool in their legs resulting in symptoms of vasovagal syncope and not SS. The relationship between vasovagal susceptibility and MS susceptibility revealed by Bosser et al. (2006), shared symptoms between MS and vasovagal syncope, and the greater peak SSQ scores of those participants who withdrew makes it difficult to distinguish whether or not the participants who withdrew in the current study experienced SS or another phenomenon, such as vasovagal syncope. In addition, participants reported to never have fainted or experienced similar sensations in their past. Furthermore, participants who withdrew never reported to have previously experienced MS.

There were no incidents of extreme responses or participant withdrawal when participants grasped the hand-rail. One possible explanation for this difference is that participants may have had more postural stability when grasping the hand-rail as compared to those participants who did not grasp the hand-rail. However, the relationship between postural stability and SS was not investigated in the current study. The postural instability theory of MS (Riccio & Stoffregen, 1991) states that the failure to maintain control of the body results in MS. It has been suggested that a simple touch of the fingertip to a stable surface can lessen postural instability and provide accurate body orientation information (Jeka & Lackner, 1995). If postural instability was a contributing influence in participant withdrawal, it is reasonable to suggest that grasping the hand-rail was enough to enhance body orientation and postural stability.

Head Movements

The design of the current study called for participants to locate an object and center it within their view (i.e. HMD display) once every 3 s. Objects were called out to participants via microcassette recorder. This was the only level of control regarding head movements in the current study. In order to assess any potential systematic condition effects related to head movements on SS, measurements of head movement velocity were obtained.

It was feasible to suspect differences in head movements between levels of update delay and levels of image scale factor. Appreciable update delays as compared to negligible update delays may cause a different behavior in head movements. Due to appreciable update delays, it may be readily perceptible that the visual scene is not moving at the same time as head movement. This incongruence between head movement and scene update does not provide the individual with accurate visual feedback relating to position or direction of movement in the VE. Therefore, when exposed to appreciable update delay, individuals may move their head in a different manner during scene update. In the current study, participants who were subjected to ~200 ms of additional update delay may have been more hesitant making head movements during scene update since they did not have accurate visual information regarding what they were viewing during these epochs.

As discussed in Draper (1998) and Draper et al. (2001), there is another consequence of image scale factor other than scene magnification and minification. Optic flow also varies with image scale factor (Draper, 1998; Draper et al., 2001) Optic flow is increased when there is scene magnification, or an image scale factor greater than 1, as compared to scene unity or minification (image scale factor ≤ 1). When scene magnification or minification occurs in a VE, the degree of head movement in the real-world is not congruent with the simulated movement in the VE. With an image scale factor of 2 (magnification), a head movement of 1° in the real-world would result in a 2° movement of the scene in the VE (Morphew, Shively, & Casey, 2004). Therefore, optic flow is increased when the scene is magnified. As a result of the perceived increase in optic flow velocity in the VE, head movement velocity may be expected to differ as a function of image scale factor (Draper, 1998; Draper et al., 2001).

Head movement velocities obtained in the current study suggested several of the abovementioned systematic differences relating to head movement. Participants moved their head at a greater velocity with an image scale factor of 2 as compared to .88. Due to the magnification effect associated with the image scale factor of 2, participants may have overshot their target (i.e. swept past the object) in the current study, resulting in a quick and corrective head movement. Albeit marginally significant, this finding is inconsistent with Draper's (1998) results. Draper (1998) did not reveal any differences in head movement velocity between image scale factors of .5, 1, or 2. No main effects of update delay or peripheral vision were revealed on head movement velocity. Also, the effect of update delay on head movement velocity was dependent on the level of peripheral vision with the greatest velocity occurring with ~200 ms of additional update delay and peripheral vision occlusion, suggested by the significant update delay X peripheral vision interaction. Furthermore, the effect of image scale factor on head movement velocity was dependent on the level of peripheral vision with the greatest velocity occurring with an image scale factor of 2 and peripheral vision occlusion, suggested by the significant image scale factor X peripheral vision interaction. Peripheral vision occlusion may have enhanced the perceptibility of the scene distortions produced by the image scale factor of 2 and the additional update delay of ~200 ms. It is possible that the quicker head movements may have resulted from corrective head movements due to sweeping past the target.

It does not appear that these differences in head movement velocities had any effects on SS since none of the above mentioned effects were observed in the current study on SS. In further support that differences in head movement velocity did not have an effect on SS in the current study, there was no observed correlation between head movement velocity and peak SSQ scores. In fact, the correlation was small, $r(77) = -.13$. These findings are also consistent to Walker (2008). While participants were moving their head, Walker (2008) did not reveal any differences in active head movements on SS while performing a task in an HMD VE.

General Discussion

As all Human Factors psychologists and engineers know, more technology does not always equal better. Designers of HMD VEs have been motivated to build more realistic VEs with increased fidelity. In theory, more realistic VEs and higher-fidelity VEs will provide for a greater feeling of ‘presence.’ The desire for designers to build more realistic HMD VEs has directed designers to constantly attempt to make HMD VEs with wider FOVs, increased display resolution, and an overall more detailed representation of the simulated environment. However, as also pointed out by Kennedy et al. (2003), much of this desire to build more realistic HMD VEs has been driven by the underlying assumption that more realistic HMD VEs will result in better and faster training without much support from empirical findings. Research is lacking regarding the relationship between fidelity, or realism, and training performance (Kennedy et al., 2003). It can be assumed that advancements in the arenas of simulation and VEs have been driven by technological advancements rather than need supported by empirical research.

HMDs and Simulator Sickness

Recently, the desire to increase realism, fidelity, and presence has heavily influenced design goals regarding HMD VEs. It is reasonable to expect that increasing overall realism will not come without a consequence of experienced SS. Kennedy et al. (2003) also hypothesized that the experience of SS will likely become more common as HMD VEs become more realistic. The consequence of increased realism can be seen in the existence of greater update delays. Increasing realism by providing wider FOVs and greater resolution, among others, is associated with greater computational, processing, and transport times within an HMD VE. With all things being equal, the end result of these increases in associated computational times is greater update delays. The result of greater update delays can be seen in a potential for a greater degree of sensory conflict between the vestibular and visual systems, manifesting in SS, as demonstrated by the current study, DiZio and Lackner (1997), and Jennings et al. (2004).

Increases in update delays are not the only consequences of increasing realism by widening FOVs within HMD VEs. As first discussed by Draper (1998) and Draper et al. (2001), the discrepancy between GFOV and physical FOV (image scale factor) has often been neglected in the research. Although not revealed in the current study, image scale factor may have further design implications regarding SS and presence that has not been adequately addressed. Therefore, designers need to be aware that there are consequences when altering physical FOVs and GFOVs in their attempt to achieve more realism and presence. Scene distortions, specifically magnification or minification, occur when independently altering either GFOV or physical FOV. Designers need to be aware that there is an existence of potential consequences other than proposed increase realism when widening physical FOV or GFOV.

Furthermore, isolation from external stimuli is thought to be a contributing component of presence (Slater et al., 1996; Witmer & Singer, 1998). As suggested by the current study, greater SS was elicited when peripheral vision was occluded (i.e. isolation from external visual stimuli). This is another example of the trade-off between providing more realism, or presence, and SS. When peripheral vision was occluded, the consequences of update delay and other possible detrimental effects of the HMD display were more apparent. Peripheral vision occlusion from the external environment can also occur in another way besides the manner in which it was obtained in the current study. HMD VEs that provide wider physical FOVs and in theory, provide more realism and presence will also occlude more peripheral vision from the external environment than HMD VEs with narrower physical FOVs. Reduced SS in DiZio and Lackner (1997) may have been observed because of a lesser degree of peripheral vision occlusion, and hence a lesser degree of sensory conflict rather than simply a narrower FOV. Therefore, designers should also consider how isolation from visual stimuli stemming from the real-world contributes to a potential sensory conflict resulting in SS. The findings herein suggests that when in an HMD VE application that involves head movements, leaving a degree of external visual information available to the user may reduce the conflict in motion detection between the visual and vestibular systems, lessening SS.

HMDs and Presence

If designers truly set forth to build HMD VEs that provide presence, designers may want to take a within-subject design approach to asses presence. As seen with the comparison of the current study to a previous study conducted in the laboratory (Moss et al. 2008), an adequate assessment of presence may only be achieved when users are able to compare their experiences to previous experiences in the HMD VE. Presence may not be a construct that can be adequately assessed at one point in time. It may be the case that comparisons have to be made in order for designers to get an accurate assessment of how much presence is provided by their HMD VE. The findings of the current study demonstrated that felt presence was unaltered by typical characteristics of HMD VEs; update delay, image scale factor, or peripheral vision.

The presence construct may not be useful when the simulated environment mimics or is based upon the current physical environment. Presence, or the experience of “being there”, may only be attainable when the simulated environment and the physical environment are dissimilar. An individual may simply not think he or she is “there” when the “there” is extremely similar to the current “here.” More presence may exist or be felt when an individual is in an unlikely, or an unfamiliar environment, e.g., an individual may feel more presence when the VE is ‘cartoonish,’ like in a video game when the individual is performing tasks in a futuristic world. Contrast this to using an HMD VE for a simulated training scenario in a real-world setting to improve your golf swing. Simulated environments may be too similar or usual to distinguish “being anywhere” other than where you currently are. Nonetheless, if designers are motivated by achieving presence, they must be aware that there still remains uncertainty as to what presence entails. Literature has discussed what presence is theoretically, but much empirical work is still necessary to support and strengthen the theoretical groundwork of presence. In addition, a consistent measure of presence needs further development and validation to extend the discussion of presence from the theoretical to the applicable and practical setting.

HMD VE designers should decide on their goals when building an HMD VE; Building a less sickening HMD VE, or building an HMD VE with increased realism and, or presence. As discussed, building an HMD VE with a greater degree of realism as its goal may come with the consequence of SS. To date, it is the current researcher’s contention that designers should attempt to reduce SS rather than increase realism, and or presence since there is relatively little known and uncertainty regarding the importance of the relationship between presence and performance other than theoretical assumptions. Coupling that contention is the inconsistent measures of presence within the literature and the less than optimal validity of current presence measures, a la the PQ. However, there is more known regarding SS and the effects of update delay. Presence is a moot point if one is experiencing severe and debilitating affect from SS causing withdrawal and lack of user acceptance of the HMD VE. However, the current researcher is not dismissing the ambition to build more realistic VEs in its entirety. For example, for entertainment purposes such as gaming, it may and most likely be necessary to provide the most realism and fidelity as technology permits to keep competitive in the gaming arena. The consequences of SS in a gamer at home may not outweigh the pure entertainment enjoyment provided by the realistic VE. Even if a gamer experiences SS, the gamer may terminate use at any time or feel the 'cost' does not outweigh the 'benefit' of entertainment value. With that said, this may not be so with highly trained professionals such as aviators whose HMD VE use is for serious and real-life applications where performance and consequences matter. The relatively minimal research indicating a link between training and performance to realism and presence, coupled with the immaturity of the presence construct suggests eradicating the negative consequences of SS should be of importance in these cases. Taken together, designers of HMD VEs should consider their primary users and the consequences of any negative effect on those users in their designs. The "latest and greatest" VE may be important for gamers and remaining competitive in the entertainment market, but detrimental for highly skilled professionals.

The current study was one of the first studies to examine multiple characteristics of HMDs and any interaction effects as well as the only study that the current researcher is aware of to use a real-world captured image rather than a 'true' computer generated VE to examine SS. Draper et al. (2001) investigated both update delay and image scale factor, but in two separate experiments. Recall an initial thought, and hence the initial inspiration for the current study, was that if update delay truly caused SS in VEs, then the same effect should be apparent when viewing a real-world image. This was revealed in the current study. Participants were more likely to be 'sick' when they were exposed to an additional update delay of ~200 ms. It is reasonable to expect problems associated with update delays in HMD VEs to always exist. With the constant attempt to increase realism and fidelity in HMD VEs, associated increases in processing and computational times to achieve such desired fidelity and realism will exist. Therefore, other intervening measures may be necessary to reduce SS. One such intervening measure, as suggested in the current study, may be a certain degree of peripheral vision inclusion.

Limitations and Future Work

Several limitations existed in the current study. One limitation was that the current study was a between-subjects design. Individual differences may have influenced the findings of the current study, especially in regards to presence. Due to time constraints and potential habituation effects, a between-subjects design was used. A second limitation was that the inherent update delay of the HMD was not known. Hence the results are limited to concluding an additional update delay of ~200 ms elicited greater SS without knowing how much total update delay existed. A third limitation of the current study was the absence of a postural stability measurement. A postural stability measurement may have provided empirical insight into the explanation of participant withdrawal when not grasping the hand-rail. A fourth limitation was the late implementation of the hand-rail. Since the use of the hand-rail was equally divided among the 80 participants and not part of the factorial design, interaction effects of grasping the hand-rail were not examined. A fifth limitation was the three extreme values obtained for peak SSQ scores. This provided for an unclear effect of update delay on SS related to the ANOVA analysis. However, the exploratory and follow up chi-square analysis provided a degree of clarity which supported the hypothesized effect of update delay on SS. A final limitation was that the current paradigm may not be appropriate for the examination of presence. The depicted scene in the HMD was the real-world image of the physical locale that participants were in. According to Witmer and Singer (1998), presence is the subjective feeling of ‘being there’ or ‘in’ a locale other than the locale that the individual is physically in.

Future research may benefit from using a within-subjects design as well as obtaining a measurement of postural stability. Knowing the inherent update delay of the system is critical. This investigation is currently in progress. It would be interesting to examine multiple levels of peripheral vision other than simply occlusion and inclusion in an attempt to identify how much peripheral vision is necessary to diminish the negative effects of update delay. Examination into the extreme responses and participant withdrawal warrants further exploration in an attempt to explain these observations as SS or a separate phenomenon. It would be interesting to examine if those extreme responses and participant withdrawal would continue at the same rate in a full study while standing freely. Even though update delay was demonstrated to have an effect on SS in the current study, future research should further explore the critical amount of update delay necessary to elicit SS. A possible attempt in answering that question may be the investigation of update delay detection threshold using the same paradigm as the current study. Once thresholds are obtained from participants, they should be subjected to their individual update delay detection threshold while performing the same task as in the current study at a later date. This may offer insight into the existence of a critical amount of update delay necessary to elicit SS and if this critical amount is an individual’s update delay detection threshold.

In general, researchers in the fields of SS and presence should strive for more consistent measurements of both SS and presence in order to develop a standard of measurement. Although more consistency exists with the use of the SSQ to measure SS, the measurement of presence is a “mixed bag” within the literature. The inconsistency regarding presence measurements makes it difficult to compare and contrast literature addressing presence. Presence needs to be further examined to develop a stronger measurement with increased validity. Until then, it will continue to be difficult to make strong inferences and conclusions from the literature regarding presence.

Conclusion

Although all the specific hypotheses of the current study were not supported, the primary research question of what characteristics of an HMD elicit SS was answered. Peripheral vision occlusion, as revealed by the significant main effect on SS, and additional update delay, as revealed by the significant chi-square test of independence, elicited SS in the current study. The significant main effect of update delay and the marginally significant main effect of peripheral vision when the extreme values were removed from the ANOVA analysis further supported the above. In addition, it was demonstrated that a significant negative relationship existed between SS and presence. This addressed the second objective of the current study which was to identify if any relationship existed between SS and presence.

The current study offers several insights as how to reduce the experience of SS when in an HMD VE. First, HMDs should not occlude all peripheral vision. Users should have some peripheral vision of the external environment, especially when appreciable update delays exist. When peripheral vision is occluded, users of HMDs are enslaved to the consequences of the HMD display, specifically, update delay. Providing peripheral vision of the external environment will provide visual motion information congruent to motion information provided by the vestibular system, reducing the sensory conflict between the visual and vestibular systems. Second, designers of HMDs should continue to strive to reduce update delays. Finally, when using an HMD, users should not stand freely. Users should be provided with something to enhance postural support such as a railing to grasp or lean up against that provides a connection to the stable external environment.

APPENDICES

Appendix A:

Consent Form

Consent Form for Participation in a Research Study
Clemson University

Effects of Helmet-Mounted Display Characteristics on User Experience

Description of the research and your participation

You are invited to participate in a research study conducted by Dr. Eric R. Muth and Jason Moss. The purpose of this research is to examine the effects changing various helmet-mounted display characteristics such as size and speed of the display on a user's experience with the display.

Your participation will involve:

1. Wearing an helmet-mounted display (HMD) through which you will view either objects in the real world or imaginary objects in a simulated world. An HMD is a video display that is worn on your head like a small set of binoculars. To limit your vision to only the HMD video display, you may wear goggles under the HMD similar to swimming goggles.

2. Making a series of timed head movements as you view various objects located in either the real or simulated world that you are looking at.

3. Possibly having your respiration, heart rate, stomach activity or eye movements monitored during the study. If you do, at the beginning of the study you will have 3 adhesive patches placed on your skin over your stomach. You will have 2 additional patches placed, one on your right shoulder and one on your left side to measure your heart rate. You will have an adhesive patch placed on your right and left temple and your forehead to monitor your eye movements. You will also wear a band around your chest to measure your breathing.

4. Completing several questionnaires asking you questions about your personal health history and motion sickness experiences.

There will be approximately 200 participants in this study. It will take you approximately 1 hour to complete this study. You may be asked to complete this study multiple times.

Risks and discomforts

By participating in this study, you may exhibit none/some/all of the following symptoms: dizziness, weakness, nausea, headache, vomiting. These symptoms will go away when the HMD is removed.

You may develop a minor skin irritation from the patches used for recording heart rate, stomach activity or eye movements.

Exclusion Criteria

If you have any known heart, brain or inner ear disorders, you are asked not to participate in this study.

If you are pregnant, you are asked not to participate in this study.

Potential benefits

By participating in this study, you may receive a monetary payment or course extra credit.

The major benefit of this study is that it will lead to a better understanding of which characteristics of HMDs make them more user friendly. There are very few published studies examining design characteristics of HMDs. Studying these characteristics will lead to better HMD design for both military and civilian applications.

Protection of confidentiality

We will do everything we can to protect your privacy. Your name and the information collected from you for the study will be kept in separate locked locations such that your name and the information that is collected from you are not linked in an easy manner. Your identity will not be revealed in any publication that might result from this study or shared without your permission.

In rare cases, a research study will be evaluated by an oversight agency, such as the Clemson University Institutional Review Board or the federal Office for Human Research Protections, that would require that we share the information we collect from you. If this happens, the information would only be used to determine if we conducted this study properly and adequately protected your rights as a participant.

Voluntary participation

Your participation in this research study is voluntary. You may choose not to participate and you may withdraw your consent to participate at any time. You will not be penalized in any way should you decide not to participate or to withdraw from this study.

Contact information

If you have any questions or concerns about this study or if any problems arise, please contact Dr. Eric R. Muth at Clemson University at 864-656-6741. If you have any questions or concerns about your rights as a research participant, please contact the Clemson University Institutional Review Board at 864-656-6460.

Consent

I have read this consent form and have been given the opportunity to ask questions. I give my consent to participate in this study.

Participant's signature: ________________________________ Date: ______________

A copy of this consent form should be given to you.

==

In addition to my consent to participate, I further give the Principal Investigator permission to share the information collected as part of this study, but not my identity, with LT Joseph Cohn and Dr. Roy Stripling of the Naval Research Laboratory, Washington, DC, and Dr. William Becker of the Naval Post Graduate School, Monterey, CA. Data will be shared for the purposes of ongoing joint data analyses for an undetermined amount of time.

☐ Yes, I give my permission.

☐ No, I do not give my permission.

PARTICIPANT'S SIGNATURE: ________________________________
DATE: __________

Appendix B

Screening Questionnaire

Subject Number:__________________Date:________________

Screening Questions

Questions	Answers	Comments
Any stomach problems?	Y / N	
Any heart problems?	Y / N	
Any brain problems?	Y / N	
Any visual problems (other than glasses)?	Y / N	
Do you have any inner ear problems?	Y / N	
Do you smoke?	Y / N	
If female, are you pregnant?	Y / N	
Currently taking any medication?	Y / N	
Do you have any experience with helmet-mounted displays?	Y / N	
Do you have any experience with virtual reality simulators/environments?	Y / N	
Do you have vertigo?	Y / N	
Do you easily get motion sick?	Y / N	
Gender:	M / F	
Ethnicity:		
Height: Weight:	Age:	

Instructions for participants.

1. No vigorous exercising for at least 1 hour before the experiment.
2. No smoking or using any tobacco product, drinking alcohol, or drinking caffeine for at least 8 hours before the experiment

Appendix C

Motion Sickness History Questionnaire (MSHQ)

SUBJECT NUMBER________ GENDER_____ DATE_________

INTRODUCTION:
This questionnaire is designed to determine:
(a) how susceptible to motion sickness you are, and
(b) what sorts of motion are most effective in causing that sickness

QUESTIONNAIRE:
1. Indicate approximately how often you have traveled on each type of transportation by using one of the following numbers:

0 = no experience 1 = fewer than 5 trips 2 = between 5 and 10 trips 3 = more than 10 trips

Cars_____	Ships_____
Buses_____	Swings_____
Trains_____	Amusement
Airplanes_____	Rides_____
Small Boats_____	Others (specify)_____

Considering only those types of transport that you have marked 1, 2, or 3 (those that you have traveled on) go on to answer the two questions below. (Use the following letters to indicate the appropriate category of response):

N = Never R = Rarely S = Sometimes F =Frequently A = Always

2. How often did you feel sick while traveling? (i.e., queasy or nauseated?)

Cars_____	Ships_____
Buses_____	Swings_____
Trains_____	Amusement
Airplanes_____	Rides_____
Small Boats_____	Others (specify)_____

3. How often were you actually sick while traveling? (i.e., vomiting?)

Cars_____	Ships_____
Buses_____	Swings_____
Trains_____	Amusement
Airplanes_____	Rides_____
Small Boats_____	Others (specify)_____

Appendix D

Simulator Sickness Questionnaire (SSQ)

Subject Number: Date: Session:

Directions: Rate your experience of the following (i.e., right now I feel:)

1.	General discomfort	(N,O)	None____Slight____Moderate____Severe____
2.	Fatigue	(O)	None____Slight____Moderate____Severe____
3.	Headache	(O)	None____Slight____Moderate____Severe____
4.	Eyestrain	(O)	None____Slight____Moderate____Severe____
5.	Difficulty focusing	(O,D)	None____Slight____Moderate____Severe____
6.	Increased salivation	(N)	None____Slight____Moderate____Severe____
7.	Sweating	(N)	None____Slight____Moderate____Severe____
8.	Nausea	(N)	None____Slight____Moderate____Severe____
9.	Difficulty concentrating	(N,O)	None____Slight____Moderate____Severe____
10.	Fullness of head	(D)	None____Slight____Moderate____Severe____
11.	Blurred vision	(O,D)	None____Slight____Moderate____Severe____
12.	Dizzy (eyes open)	(D)	None____Slight____Moderate____Severe____
13.	Dizzy (eyes closed)	(D)	None____Slight____Moderate____Severe____
14.	Vertigo	(D)	None____Slight____Moderate____Severe____
15.	Stomach awareness	(N)	None____Slight____Moderate____Severe____
16.	Burping	(N)	None____Slight____Moderate____Severe____

N = Nausea item, O = Oculomotor item, D = Disorientation item

Appendix E

Presence Questionnaire

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer. **Answer in relation to when you were performing the experiment wearing the HMD.**

WITH REGARD TO THE EXPERIENCED ENVIRONMENT (WEARING THE HMD)

1. How much were you able to control events?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

2. How responsive was the environment to actions that you initiated (or performed)?

|________|________|________|________|________|________|________|
NOT RESPONSIVE MODERATELY RESPONSIVE COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?

|________|________|________|________|________|________|________|
EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

4. How much did the visual aspects of the environment involve you?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

5. How much did the auditory aspects of the environment involve you?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

6. How natural was the mechanism which controlled movement through the environment?

|________|________|________|________|________|________|________|

EXTREMELY ARTIFICIAL	BORDERLINE	COMPLETELY NATURAL

7. How compelling was your sense of objects moving through space?

|________|________|________|________|________|________|________|

NOT AT ALL	MODERATELY COMPELLING	VERY COMPELLING

8. How much did your experiences in the virtual environment seem consistent with your real world experiences?

|________|________|________|________|________|________|________|

NOT CONSISTENT	MODERATELY CONSISTENT	VERY CONSISTENT

9. Were you able to anticipate what would happen next in response to the actions that you performed?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	COMPLETELY

10. How completely were you able to actively survey or search the environment using vision?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	COMPLETELY

11. How well could you identify sounds?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	COMPLETELY

12. How well could you localize sounds?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	COMPLETELY

13. How well could you actively survey or search the virtual environment using touch?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	COMPLETELY

14. How compelling was your sense of moving around inside the virtual environment?

|________|________|________|________|________|________|________|

NOT COMPELLING	MODERATELY COMPELLING	VERY COMPELLING

15. How closely were you able to examine objects?

|________|________|________|________|________|________|________|

NOT AT ALL	PRETTY CLOSELY	VERY CLOSELY

16. How well could you examine objects from multiple viewpoints?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	EXTENSIVELY

17. How well could you move or manipulate objects in the virtual environment?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	EXTENSIVELY

18. How involved were you in the virtual environment experience?

|________|________|________|________|________|________|________|

NOT INVOLVED	MILDLY INVOLVED	COMPLETELY ENGROSSED

19. How much delay did you experience between your actions and expected outcomes?

|________|________|________|________|________|________|________|

NO DELAYS	MODERATE DELAYS	LONG DELAYS

20. How quickly did you adjust to the virtual environment experience?

|________|________|________|________|________|________|________|

NOT AT ALL	SLOWLY	LESS THAN ONE MINUTE

21. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

|________|________|________|________|________|________|________|
NOT PROFICIENT — REASONABLY PROFICIENT — VERY PROFICIENT

22. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

|________|________|________|________|________|________|________|
NOT AT ALL — INTERFERED SOMEWHAT — PREVENTED TASK PERFORMANCE

23. How much did the control devices interfere with the performance of assigned tasks or with other activities?

|________|________|________|________|________|________|________|
NOT AT ALL — INTERFERED SOMEWHAT — INTERFERED GREATLY

24. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

|________|________|________|________|________|________|________|
NOT AT ALL — SOMEWHAT — COMPLETELY

25. How completely were your senses engaged in this experience?

|________|________|________|________|________|________|________|
NOT ENGAGED — MILDLY ENGAGED — COMPLETELY ENGAGED

29. How easy was it to identify objects through physical interaction; like touching an object, walking over a surface, or bumping into a wall or object?

|________|________|________|________|________|________|________|
IMPOSSIBLE — MODERATELY DIFFICULT — VERY EASY

30. Were there moments during the virtual environment experience when you felt completely focused on the task or environment?

|________|________|________|________|________|________|________|
NONE OCCASIONALLY FREQUENTLY

31. How easily did you adjust to the control devices used to interact with the virtual environment?

|________|________|________|________|________|________|________|
DIFFICULT MODERATE EASILY

32. Was the information provided through different senses in the virtual environment (e.g., vision, hearing, touch) consistent?

|________|________|________|________|________|________|________|
NOT CONSISTENT SOMEWHAT CONSISTENT VERY CONSISTENT

There are 4 subscales:

Involvement – 1, 2, 3, 4, 6, 7, 8, 10, 14, 17, 18, 29
Sensory Fidelity – 5, 11, 12, 13, 15, 16
Adaptation/Immersion – 9, 20, 21, 24, 25, 30, 31, 32
Interface Quality – 19, 22, 23

Note: The numbering of the above items is consistent with version 3.0 of the Presence Questionnaire. However, the items themselves are from version 4.0.

Appendix F

Head Movement Accuracy Checklist

Correct: Object centered on display, participant moved directly to object.
Opposite Direction: Participant initially turned head in opposite direction of object.
Incorrect: Looked at wrong object.
Lost: Did not center object on display before next object was called.

TRIAL #1

Movement #	Moving to:	Correct	Opposite	Incorrect	Lost	Comments
1	Left Clock					
2	Right First Aid					
3	Right Curtain					
4	Left Front Door					
5	Right Fan					
6	Left Fire Ext.					
7	Right Front Door					
8	Right Fan					
9	Right Curtain					
10	Left Clock					
11	Right Flag					
12	Left Office Door					
13	Right Fan					
14	Left Flag					
15	Left Office Door					
16	Right Curtain					
17	Left Fire Ext.					
18	Right First Aid					
19	Left Fire Ext.					
20	Right Fan					
21	Left Clock					
22	Right Curtain					
23	Left Clock					
24	Right Flag					
25	Right Curtain					
26	Left Fire Ext.					
27	Left Flag					
28	Right Fan					
29	Left Front Door					
30	Left Fire Ext.					
31	Right Front Door					
32	Right Curtain					
33	Left Front Door					
34	Left Clock					
35	Right Curtain					
36	Left Fire Ext.					
37	Left Office Door					

38	Right Flag					
39	Right Fan					
40	Left Front Door					

TRIAL #2

Movement #	Moving to:	Correct	Opposite	Incorrect	Lost	Comments
1	Right Curtain					
2	Left Office Door					
3	Right Flag					
4	Right Front Door					
5	Right First Aid					
6	Right Fan					
7	Left Office Door					
8	Right Fire Ext.					
9	Left Office Door					
10	Right Fan					
11	Left First Aid					
12	Left Clock					
13	Right Curtain					
14	Left Fire Ext.					
15	Right First Aid					
16	Right Fan					
17	Left Fire Ext.					
18	Left Office Door					
19	Right Front Door					
20	Left Fire Ext.					
21	Left Flag					
22	Left Office Door					
23	Right Fan					
24	Left Front Door					
25	Left Clock					
26	Right Fan					
27	Left Front Door					
28	Left Flag					
29	Right Curtain					
30	Left Fire Ext.					
31	Right First Aid					
32	Right Curtain					
33	Left Clock					
34	Right Front Door					
35	Right First Aid					
36	Right Curtain					
37	Left Fire Ext.					
38	Right First Aid					
39	Right Curtain					
40	Left Fan					

TRIAL #3

Movement #	Moving to:	Correct	Opposite	Incorrect	Lost	Comments
1	Left Fire Ext.					
2	Left Office Door					
3	Right First Aid					
4	Left Flag					
5	Right First Aid					
6	Left Clock					
7	Right Fan					
8	Right Curtain					
9	Left Fire Ext.					
10	Right Curtain					
11	Left Office Door					
12	Right Front Door					
13	Left Office Door					
14	Right Front Door					
15	Right Fan					
16	Left Front Door					
17	Right Curtain					
18	Left Fan					
19	Left Flag					
20	Right Curtain					
21	Left Fan					
22	Left Fire Ext.					
23	Right Curtain					
24	Left Flag					
25	Left Office Door					
26	Right Fan					
27	Left Front Door					
28	Left Clock					
29	Right First Aid					
30	Left Office Door					
31	Right Fan					
32	Left Front Door					
33	Right Curtain					
34	Left Clock					
35	Right Front Door					
36	Right Curtain					
37	Left Clock					
38	Right Flag					
39	Right Curtain					
40	Left Clock					

TRIAL #4

Movement #	Moving to:	Correct	Opposite	Incorrect	Lost	Comments
1	Right Fan					
2	Left Flag					
3	Right Fan					
4	Left First Aid					
5	Left Fire Ext.					
6	Left Flag					
7	Right First Aid					
8	Left Fire Ext.					
9	Right Curtain					
10	Left Flag					
11	Right Fan					
12	Left Flag					
13	Left Office Door					
14	Right Front Door					
15	Right Fan					
16	Left Office Door					
17	Right Fire Ext.					
18	Right Front Door					
19	Right Fan					
20	Left Fire Ext.					
21	Right Fan					
22	Left Fire Ext.					
23	Right Curtain					
24	Left Front Door					
25	Left Flag					
26	Right Fire Ext					
27	Left Office Door					
28	Right Front Door					
29	Left Office Door					
30	Right Front Door					
31	Right Fan					
32	Left Fire Ext.					
33	Right Fan					
34	Left First Aid					
35	Left Clock					
36	Right Fan					
37	Right Curtain					
38	Left First Aid					
39	Left Flag					
40	Right First Aid					

TRIAL #5

Movement #	Moving to:	Correct	Opposite	Incorrect	Lost	Comments :
1	Left Flag					
2	Right First Aid					
3	Left Front Door					
4	Right Curtain					
5	Left Front Door					
6	Right Fan					
7	Left First Aid					
8	Left Office Door					
9	Right Fan					
10	Left Office Door					
11	Right Fan					
12	Left Front Door					
13	Left Clock					
14	Right Curtain					
15	Left Fire Ext.					
16	Right First Aid					
17	Left Fire Ext.					
18	Right Fan					
19	Left Front Door					
20	Left Flag					
21	Left Clock					
22	Right First Aid					
23	Right Curtain					
24	Left First Aid					
25	Left Clock					
26	Right Fan					
27	Left Office Door					
28	Right Fan					
29	Left First Aid					
30	Left Flag					
31	Left Clock					
32	Right Fire Ext.					
33	Right First Aid					
34	Left Flag					
35	Left Clock					
36	Right Front Door					
37	Right Curtain					
38	Left First Aid					
39	Left Clock					
40	Right Flag					

Appendix G

Histograms of Peak SSQ Scores by Condition

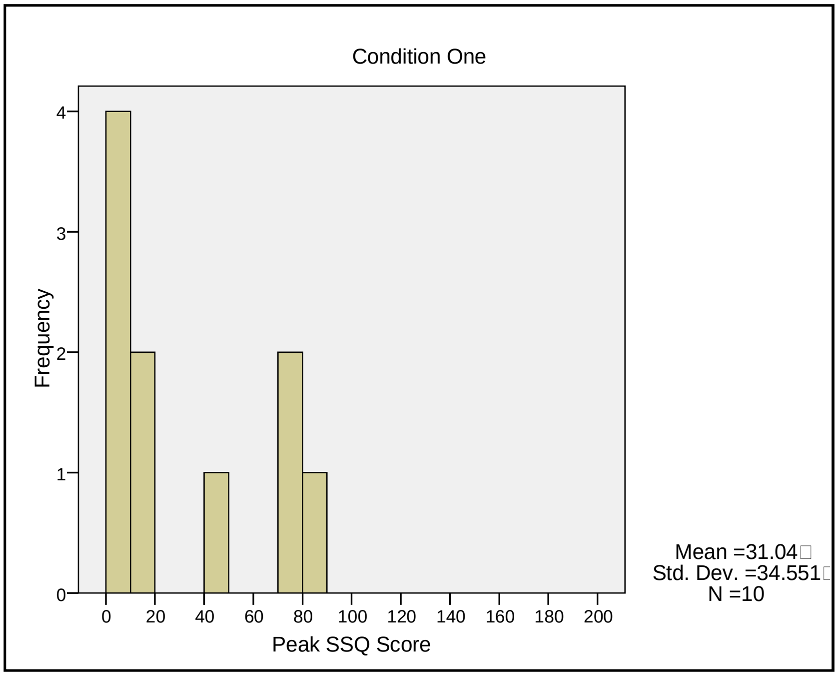

Figure G-1. Frequency distribution of peak SSQ scores for condition one.

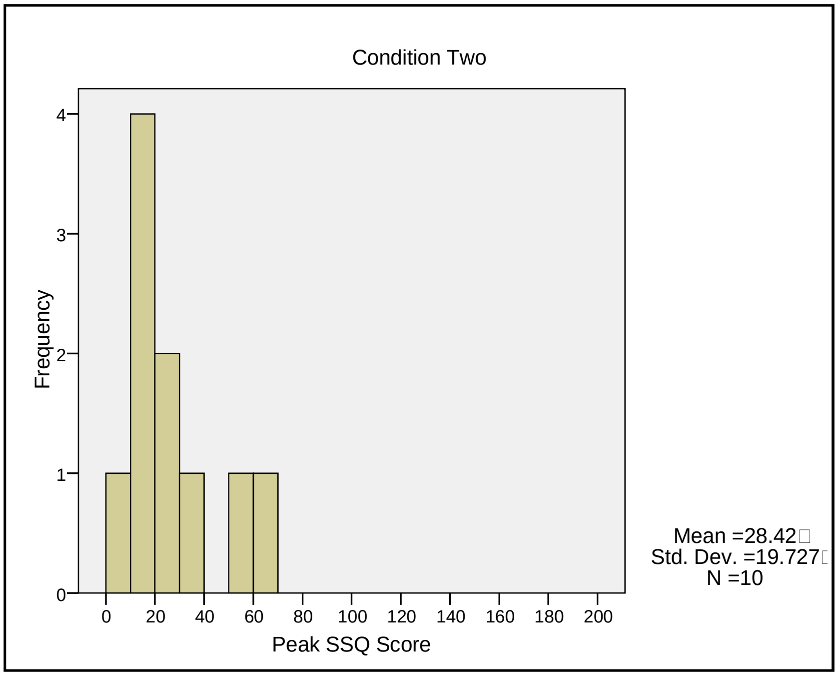

Figure G-2. Frequency distribution of peak SSQ scores for condition two.

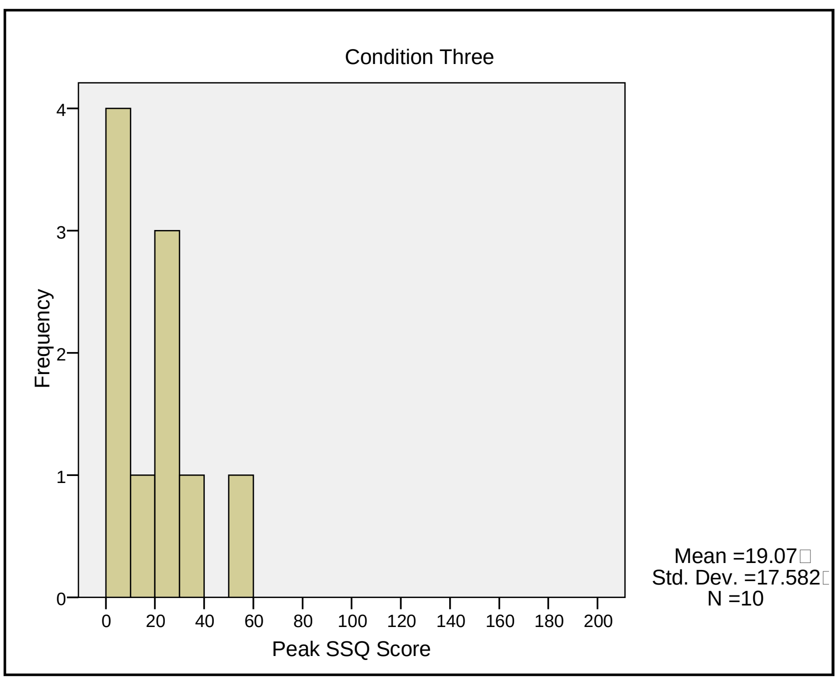

Figure G-3. Frequency distribution of peak SSQ scores for condition three.

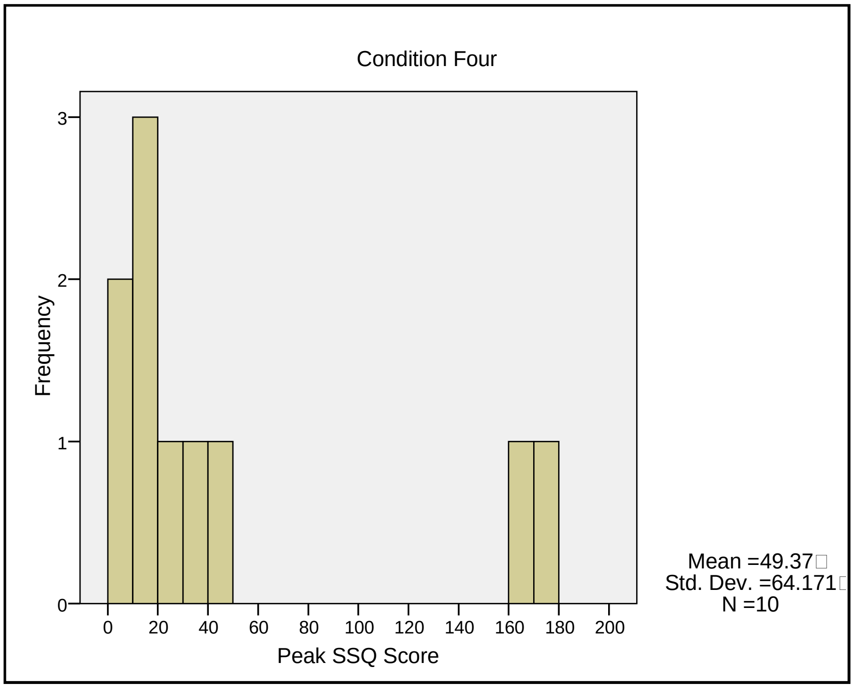

Figure G-4. Frequency distribution of peak SSQ scores for condition four.

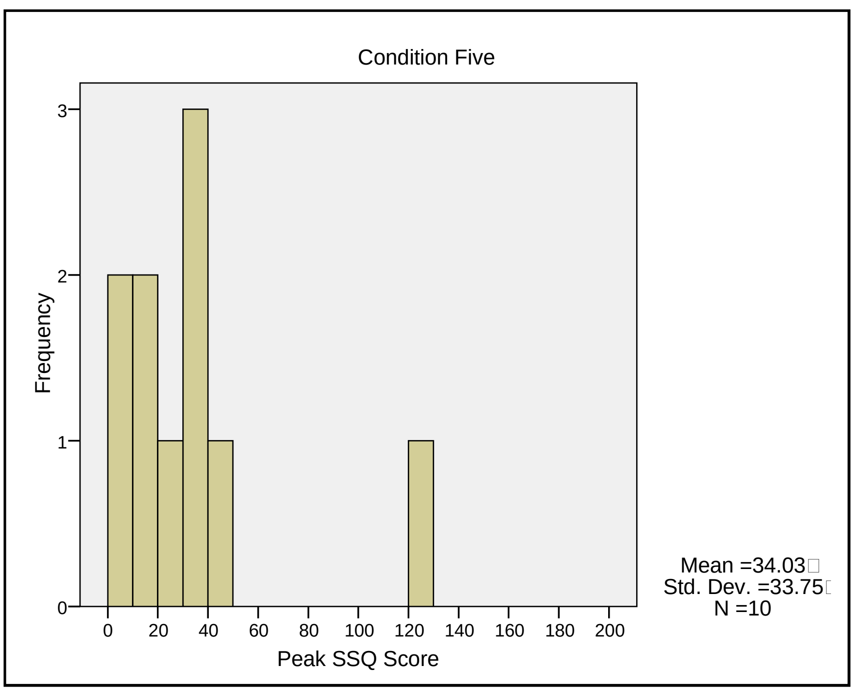

Figure G-5. Frequency distribution of peak SSQ scores for condition five.

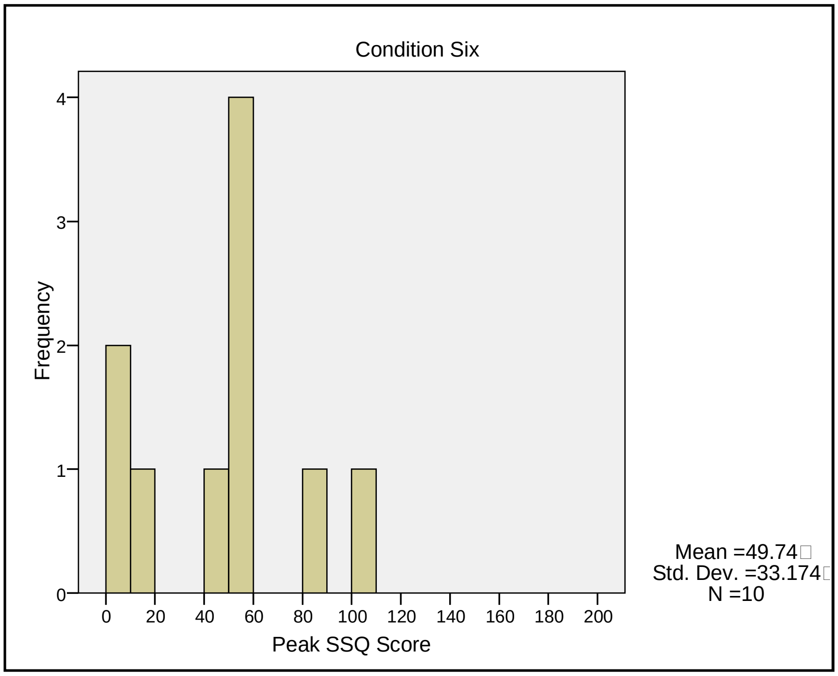

Figure G-6. Frequency distribution of peak SSQ scores for condition six.

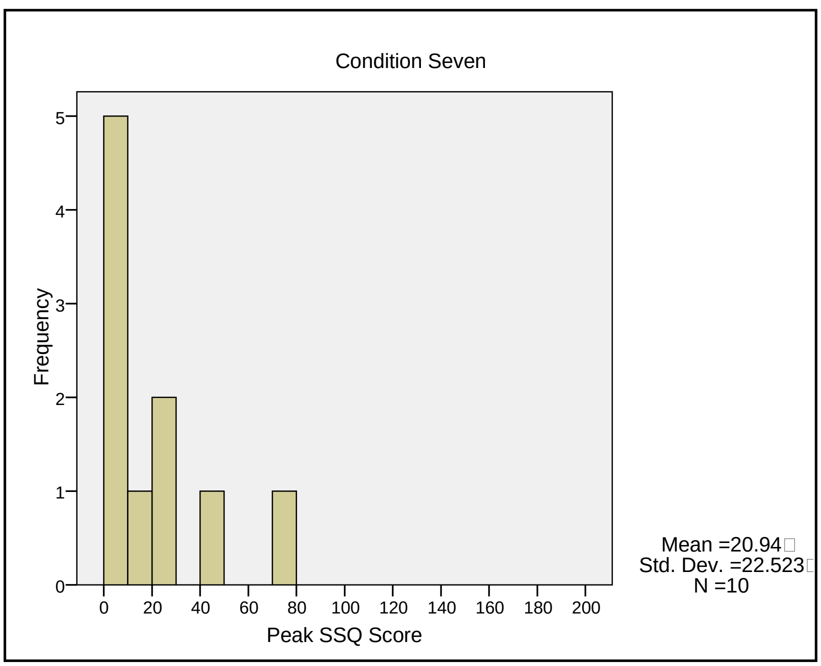

Figure G-7. Frequency distribution of peak SSQ scores for condition seven.

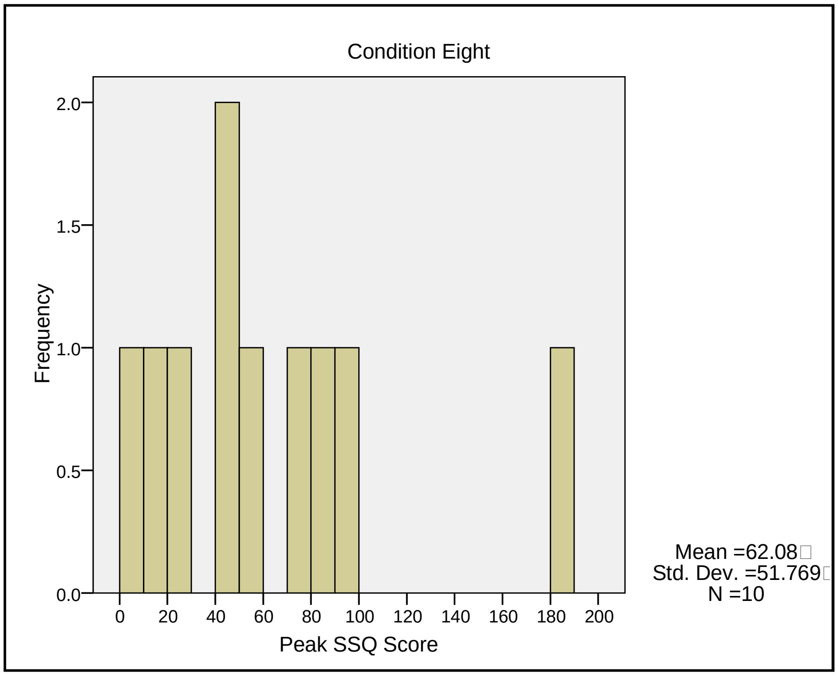

Figure G-8. Frequency distribution of peak SSQ scores for condition eight.

Appendix H

Histograms of the Square Root Transformations of Peak SSQ Scores by Condition

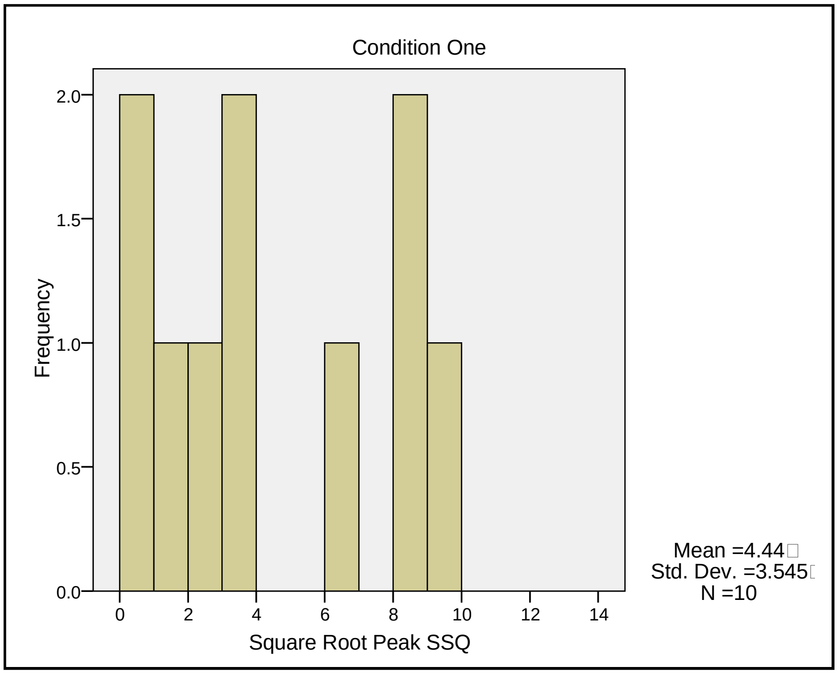

Figure H-1. Frequency distribution of square root peak SSQ scores for condition one.

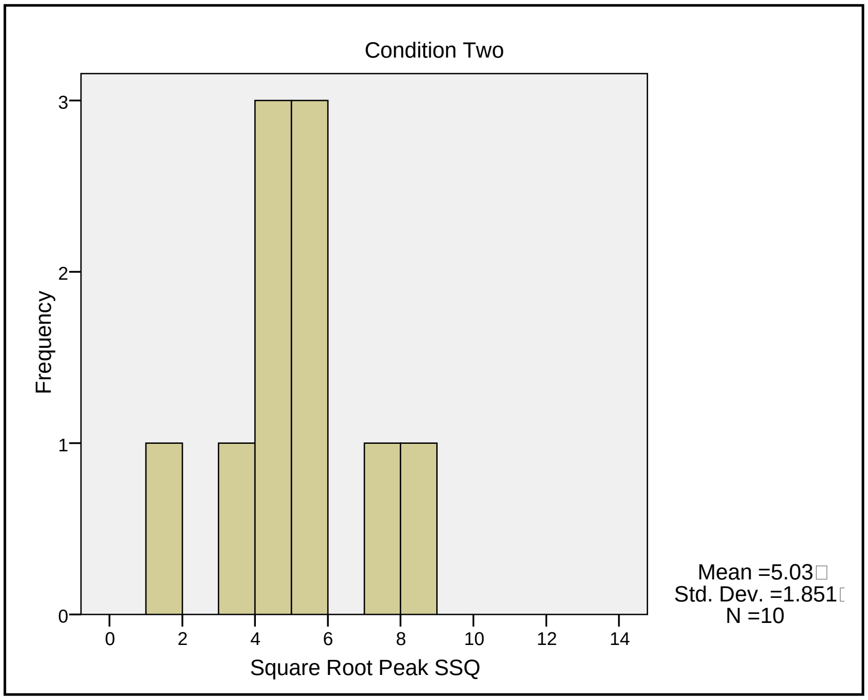

Figure H-2. Frequency distribution of square root peak SSQ scores for condition two.

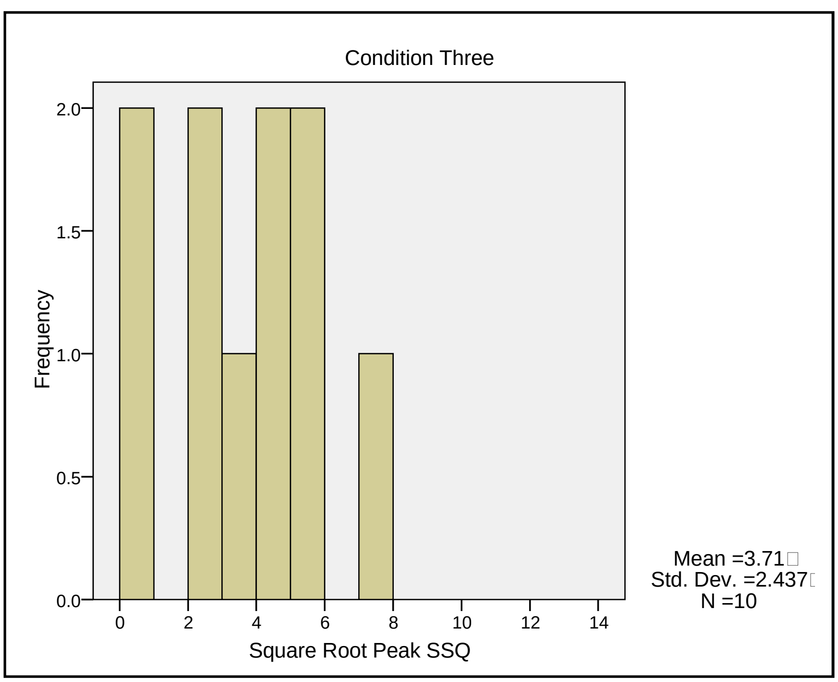

Figure H-3. Frequency distribution of square root peak SSQ scores for condition three.

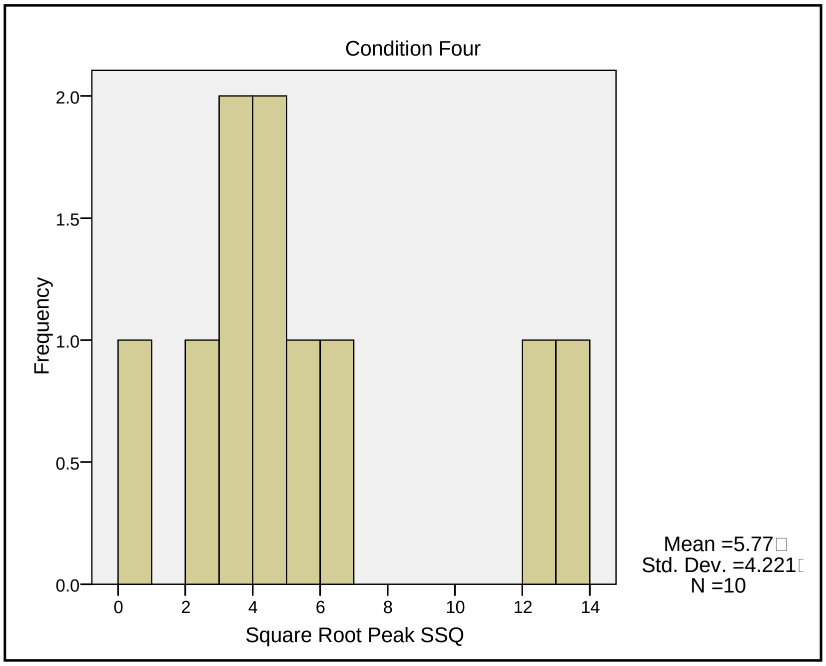

Figure H-4. Frequency distribution of square root peak SSQ scores for condition four.

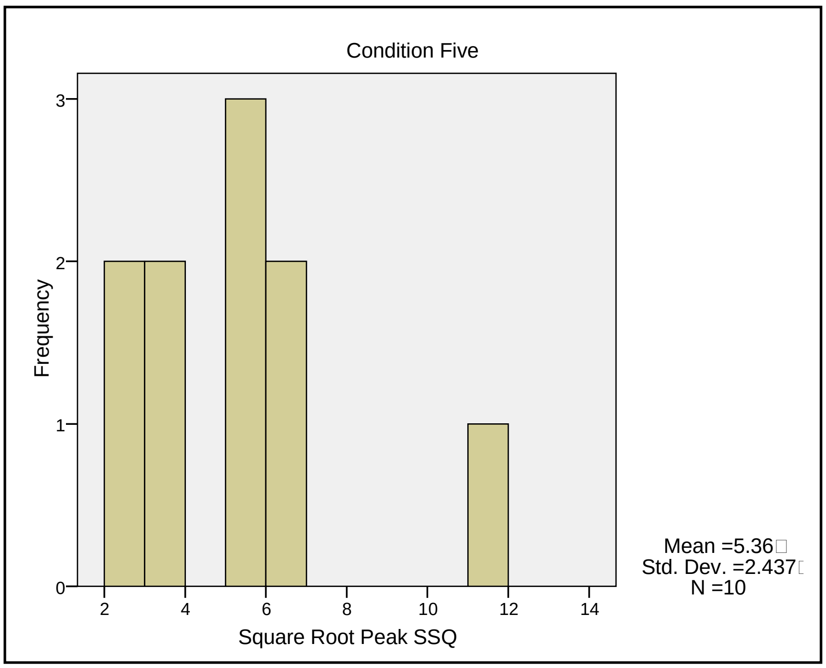

Figure H-5. Frequency distribution of square root peak SSQ scores for condition five.

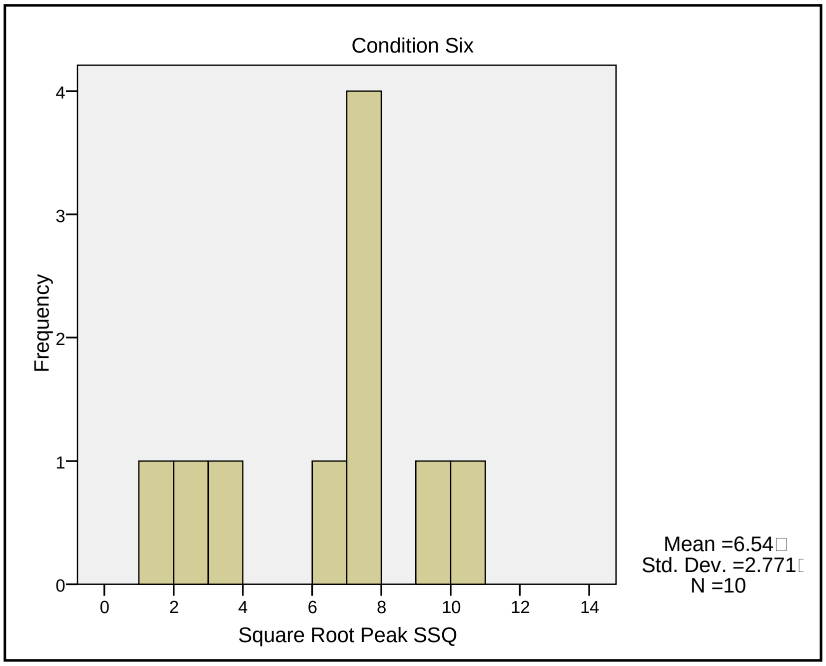

Figure H-6. Frequency distribution of square root peak SSQ scores for condition six.

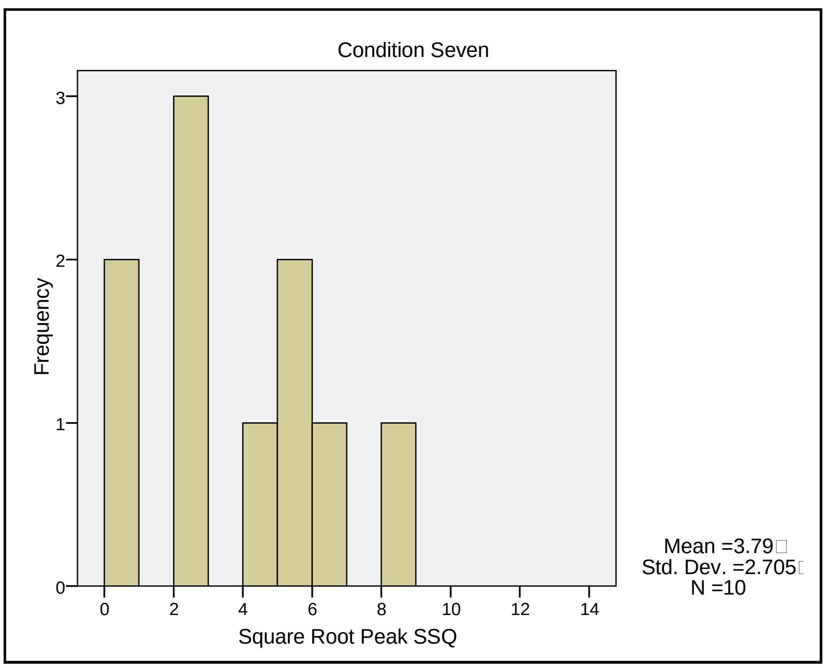

Figure H-7. Frequency distribution of square root peak SSQ scores for condition seven.

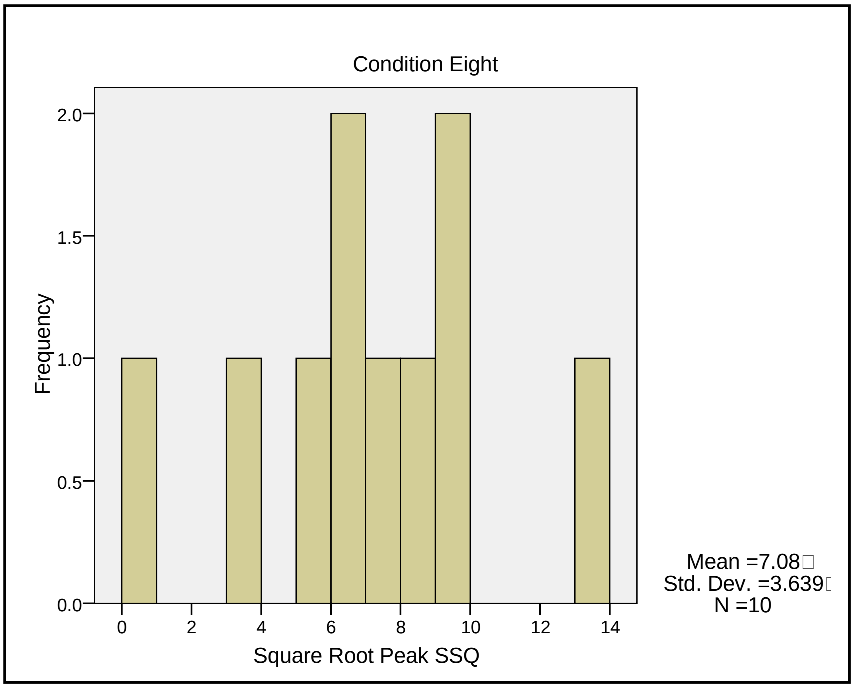

Figure H-8. Frequency distribution of square root peak SSQ scores for condition eight.

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