12-2012

THE EFFECTS OF 0.2 HZ VARYING LATENCY WITH 20-100 MS VARYING AMPLITUDE ON SIMULATOR SICKNESS IN A HELMET MOUNTED DISPLAY

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THE EFFECTS OF 0.2 HZ VARYING LATENCY WITH 20-100 MS VARYING
AMPLITUDE ON SIMULATOR SICKNESS IN A HELMET MOUNTED DISPLAY

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Human Factors Psychology

by
Matthew Edward St. Pierre
December 2012

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ABSTRACT

The relationship between the occurrence of simulator sickness (SS) and the several characteristics of latency (i.e., added latency, amplitude of latency, and frequency of latency) in a helmet-mounted display (HMD) were explored in this study. The experience of SS while using an HMD has often been attributed to system latency. These findings are typical in research where HMDs with head trackers are used. The current study explored the effects of 200 ms added constant latency, latency varying at 0.2 Hz with a constant 100 ms amplitude, and latency varying at 0.2 Hz with a 20-100 ms varying amplitude on the experience of SS in HMDs while viewing a real world scene. Participants wore a HMD and made multiple head movements while performing an object location task in the laboratory. Data sets were collected from 120 participants. Eleven participants withdrew prior to completion of the experiment. Results revealed a significant difference between SSQ peak scores in the presence of varying amplitude of latency and fixed amplitude of latency. In addition, results revealed a significant difference between SSQ peak scores in the presence of 0.2 Hz frequency of latency and 0 Hz frequency of latency. Significantly more participants dropped out before completing the experiment due to condition membership, with the varying amplitude of latency condition having 7 out of the 11 drop outs in the study. The results of this study indicated that the elimination of varying amplitude of latency may lessen the experience of SS in HMDs. HMD systems should be developed in a way that minimizes sensor error, which was found by Wu et al. (2011) to be responsible for varying amplitude and

frequency of latency. Further research should be performed to further explore the separate and combined effects of frequency and amplitude of latency in an HMD and the experience of SS.

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CHAPTER I

INTRODUCTION

The primary purpose of this work was to examine the effect of variability in system latency in a helmet mounted display (HMD), specifically variations in frequency and amplitude of latency on simulator sickness (SS). A secondary purpose was to determine the relationship between changes in the visual system due to HMD use and the propensity of an individual to experience SS symptomology.

HMDs are head-worn visual displays often used to display virtual environments (VEs). When used in VE applications, HMDs are often linked to position trackers to provide a computer with head location and orientation (Blade & Padgett, 2002). VE technology has been used to advance fields such as medicine, engineering, education, design, training, and entertainment (Stanney, Mourant, & Kennedy, 1998). VEs are often used for the purpose of training through simulation. They are often used in this capacity because real on-the-job training would be too risky for the trainee resulting in damage or loss of product, equipment, or possible death or injury to the trainee or too expensive.

Aside from the benefits of VE or HMD use, there are substantial drawbacks. Synthetic environments (SEs) such as VE have been attributed to the experience of Sospite syndrome (excessive drowsiness), loss of visual acuity during head or body motion, and postural disequilibrium (Lawson, Graeber, Mead, & Muth, 2002). One commonly documented drawback from the use of VEs is the occurrence of SS. SS is a subset of the motion sickness (MS). SS involves symptoms including headache, nausea,

dizziness, stomach discomfort, eyestrain, oscillopsia, and postural ataxia (Kennedy, Hettinger, & Lilienthal, 1990). These symptoms can make the use of HMDs uncomfortable, and in a training situation, can impact the transfer training to the real world due to the trainee adopting strategies to avoid SS that are not appropriate in the real world situation.

Research has examined both hardware and software components associated with HMDs to determine why users experience SS. Lag, a specific type of system latency, is the time between head movements and the resulting movement in the visual display, and has been linked to SS in an HMD (DiZio & Lackner, 1997). Wide field of view (FOV; DiZio & Lackner, 1997), changing image scale factor (Draper, Viirre, Furness, & Gawron, 2001) and the use of eye cups to occlude peripheral vision (Moss & Muth, 2011) have also been identified as factors contributing to SS. However, no factor has been singled out as the main driver of SS in an HMD.

The current study examined factors that have not been researched in HMDs but are known to cause motion sickness in non-VE situations. This study examined the latency inherent within the HMD system, e.g., from the sense of a head movement to the actuation of the corresponding images within the HMD displays. Latency is typically thought of as a constant and reported by system developers as a single number. However, a recent study by Wu, Dong, and Hoover (2011), measuring latency between sensing and actuation, determined that an orientation sensing error inherent in the system produces varying latency over time. The variation in latency associated with sensor error (e.g., head tracker error) reported by Wu et al. (2011) ranges between 0.5-1.0 Hz and is

within the frequency range known to cause MS symptoms in real moving environments (Alexander, Cotzin, Klee, & Wendt, 1947; O'Hanlon & McCauley, 1974; Lawther & Griffin, 1988; Golding, Phil, Mueller, & Gresty, 2001; Duh, Parker, Philips, & Furness, 2004). Others have also suggested that system latency varies and is not a constant (Adelstein, Johnston, & Ellis, 1996; Di Luca, 2010). However, Wu et al. (2011) is the first study to measure latency continuously at a rate sufficient to see changes over a period of less than 1 second.

The frequency region of around 0.2 Hz, has been found to produce the maximum amount of MS (Golding et al., 2001) and Golding (2006) proposed that this frequency represents a cross-over region concerning the correct frame of reference for spatial orientation from externally induced motion to self-induced motion. This zone is referred to as a zone of perceptual-motor ambiguity because human spatial reference systems interpret higher frequencies as translation of self through space whereas low frequencies are interpreted as a shift in main force vector (Golding, Bles, Bos, Haynes, & Gresty, 2003; Golding & Gresty, 2005). The frequency range from 0.5-1.0 Hz, found by Wu et al. (2011) which is inherent in the system, is near the maximum nausea frequency near 0.2 Hz (O'Hanlon & McCauley, 1974; Lawther & Griffin, 1988; Golding et al., 2001). The current study examines the effects of adding latency to an HMD system and varying the latency over time through manipulations of amplitude and frequency of latency.

CHAPTER II

BACKGROUND

Virtual Environments

Purpose of Virtual Environment Technology

While there are varying ways that VE technologies, sometimes referred to as virtual reality (VR), have been defined, Carr (1995) states that the definitions share common factors and concluded that all definitions specify that VEs simulate human perceptual experience by creating an impression of something that is not there in reality. VE technology has been exploited for a variety of purposes from recreational to training skills that are not feasible to train in a real environment. As technology becomes more advanced, the applications for VE technology have also increased.

There are many types of VEs, such as fixed-base flight or drive simulators, Cave Automatic Virtual Environments (CAVE), and HMDs. The type of VE device employed in any given application is driven by factors such as task characteristics, portability, training transfer, and technological capability of the environment. Despite the many useful applications of VE, there are several drawbacks such as SS, eyestrain, poor ergonomic design of the device, and lack of immersion/presence that limit user acceptance.

Head Mounted Displays

HMDs are head-worn personal display units used to view a real world scene or a VE. HMDs consist of a helmet with small CRTs or liquid-crystal displays (LCDs) in an individual display or pair of displays. HMDs come in monocular, binocular, or bi-ocular form. Monocular HMDs project images through a single display to one eye. Binocular HMDs project disparate images through individual displays to each eye for stereoscopic viewing. Bi-ocular HMDs utilize two displays to project identical images to both eyes. HMDs are currently used in the medical industry, for military applications, flight simulation and automobile racing, and gaming and amusement industries. Shibata (2002) identified features of HMDs:

“(1) large, wide-ranging screens are possible for vision; (2) miniaturization and weight reduction are possible for usability; (3) utility is fundamentally depending on individual preference; (4) it is possible to present interactive spatial information; and (5) it is possible to superimpose the image on an external scene by means of see-through function (p. 57).”

HMDs typically utilize head tracking to track a user's visual point of reference within the VE and adjust the visual point of view based on the tracked and measured head movements.

HMDs fail to live up to technological and interactive expectations for reasons such as a lack of display fidelity or the inability to mimic a real world environment (Keller & Colucci, 1998). User acceptance is decreased due to a host of symptoms and aftereffects, which include SS, oculomotor changes, and disorientation. A user may

experience none, one, or multiple combinations of symptoms or aftereffects from HMD use. These symptoms and aftereffects are typically viewed as the result of technological limitations or other issues that cause the HMD VE to produce an experience that is somehow different than that of the real world situation being simulated.

Technological Limitations of Head Mounted Displays

Many of the limitations of the HMD revolve around how the viewing situation in an HMD differs from a normal viewing situation. Actual FOV is smaller in an HMD as compared to the real world and full 360° FOV (called effective FOV in an HMD) which requires greater head movements in an HMD compared to in the real world. Each eye can see 140° horizontally and when the two eyes work together they view at roughly 195° (Keller & Colucci, 1998). Most HMDs advertised with a wide FOV can only view roughly 60°. Although some HMDs have the ability to view larger areas than 60°, they still fall short of the actual FOV in a real world viewing situation. Resolution may differ between the HMD and real world. Although many HMDs have excellent resolution, many do not. This lack of resolution can produce low quality images. There is often a tradeoff between HMD weight and resolution or FOV where increasing resolution or FOV leads to increased HMD weight. The weight of the HMD may impact head motion and neck strain. Further, there is an inverse between FOV and resolution.

System latency is a common problem in HMDs. Latency occurs from sensing to actuation, which is the time from the motion tracker sensing the head movement of the user to the output of updated images corresponding to head movements on the displays.

In behavioral studies this is often referred to as latency, lag, or update delay. For the purposes of this study, the concept of latency, lag, and update delay will be referred to as latency.

Visual-Vestibular Interactions in Head Mounted Displays

Vestibular Apparatus

The vestibular apparatus is a sensory organ located in the bony labyrinth of the inner ear. The purpose of this structure is to sense head movements and create response signals. Stoffregen, Draper, Kennedy, and Compton (2002) state “these signals contribute to the effective coordination of eye movements, posture and balance, and the perception of motion and orientation (p. 775).” Without proper vestibular function, simple activities such as standing, walking, or reading present great difficulty. The two structures of the vestibular apparatus are the semicircular canals (SCCs) and the otoliths, which provide information about head motion and orientation. See Figure 2.1. Each ear has its own vestibular apparatus. Vestibular signals are sent via the eighth cranial nerve to the brain and postural control nuclei.

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

Three SCCs (i.e., anterior, posterior, and horizontal canals) reside in each ear to detect angular acceleration of the head. Stoffrogen et al. (2002) says “these canals are each bi-directionally sensitive and, when combined across the two vestibules, form three approximately perpendicular “push-pull” pairs so as to detect angular head acceleration in any direction (p. 775).” Each SSC is an independent circuit containing endolymph fluid that is prevented from free flow by a thin elastic flap called the cupula. During head rotation, forces generated by the endolymph fluid viscosity and inertia act against the cupula causing it to deflect, which displaces the tiny hairs at the base of the cupula producing an efferent signal (Draper, 1996).

Each vestibular apparatus also contains two otolith organs called the utricle and saccule, which sense changes to linear acceleration of the head and provide information about head tilt. As opposed to the bi-directional nature of the SCCs, the otolith organs

are multi-directionally sensitive. The utricle is heavily influenced by horizontal linear acceleration and the saccule is heavily influenced by vertical linear acceleration. The macula is the receptor portion of the otolith organs and contains hair cells. A gelatinous substance that contains tiny calcium carbonate crystals covers the macula. These crystals of calcium carbonate are called otoliths. Stoffregen et al. (2002) describes the process by which the otolith organs detect motion as follows:

“When there is a change in the orientation of the head relative to the gravito-inertial force vector, inertia causes the otoliths to deform the gelatinous mass; this creates a shear force that bends the receptor hair cells in the macula, generating the efferent signal (p. 776).”

Vestibulo-Ocular Reflex

The vestibulo-ocular reflex (VOR) is a reflexive eye movement that serves the function of stabilizing images on the retina during head movements. This basic reflex serves a critical function allowing sight during movement. The basic process through which the VOR occurs begins with a head movement; the vestibular apparatus senses the movement and signals the oculomotor system with direction and rate information. As early as 10-20 ms later, the oculomotor system responds by making compensatory eye movements in the opposite direction and at the same rate of the head movement.

VOR adaptation has been shown to respond to changes in dynamics associated with real and virtual self-motion (Stoffregen et al., 2002). Due to motion dynamics differences between the real world and VE, the VOR must adapt to maintain gaze

stability and minimize retinal slip (movement of the visual field across the retina). The amount of VOR gain adaptation depends on the amount of retinal slip generated by altered visual-vestibular motion stimulation and exposure time. Multiple studies have shown the influence of video images in an HMD on VOR adaptation (Kramer, Roberts, Shelhamer, & Zee, 1998; Draper, 1998). Particularly, it was found that stimuli presented in an HMD can drive VOR adaptation much like conventional stimuli.

Optokinetic Reflex

Unlike VOR, the optokinetic reflex (OKR) provides gaze stability through the use of visual inputs. The OKR detects the occurrence of image slip through the use of visual inputs from the entire retina rather than the fovea only. An image slip is manifest as an optical flow field moving across the retina (Draper, 1996). This is compensated by a corrective eye movement with equal gain in the direction of the optic flow. Unlike vestibular nystagmus which requires head rotation, OKR can produce optokinetic nystagmus as long as a moving image with a large field-of-view is present. The VOR and OKR work as a synergistic system for maximal compensatory eye response to stabilize gaze during any head movement. OKR has a longer latency time than VOR. VOR reacts fast and while it decays, the OKR is building up to allow for seamless stabilization of images on the retina. In addition, OKR has no time constant so it does not decay with repeated retinal stimulation.

Nystagmus

Another reflexive movement of the eye is called nystagmus. Nystagmus is a rhythmic oscillatory pattern that the eye exhibits during exposure to certain stimuli, specifically sustained head rotation in any direction. Depending on the stimulus, various forms of nystagmus can occur such as optokinetic, vestibular, or caloric to name a few. For instance, if head rotation is in a dark environment, the nystagmus has only a vestibular input and is called vestibular nystagmus (Draper, 1996). The process of vestibular nystagmus begins when the head rotates in the horizontal plane either to the right or left. At this time VOR will compensate by moving the eyes in an equal and opposite direction. Once the eye reaches the edge of its orbit, it will rapidly reverse direction across the center of gaze. This reversal in the direction of head movement is called quick phase of nystagmus. After the quick phase movements, slower eye movements occur in the opposite direction of the head rotation. This slower movement is called the slow phase of nystagmus. The vestibular nystagmus response decays once the SCCs adapt to zero acceleration rotation input. Caloric nystagmus occurs in response to irrigation of the ears by warm or cold water or air. This type of nystagmus results in rotational eye movements, therefore sometimes being referred to as rotatory nystagmus. In a basic caloric test when an ear is irrigated with warm water, the eye makes a rotational movement in the direction of the irrigated ear. When cold water is used, the eye makes a rotational movement away from the irrigated ear.

In lighted conditions, contoured visual field rotations before a stationary observer can cause optokinetic nystagmus (OKN; May & Badcock, 2002). OKN does not decay

because of the constant input to the oculomotor system. In OKN, the eyes move to follow the direction of rotation (slow phase) and then snap back in the opposite direction (fast phase). This pattern repeats itself in bursts with short periods of gaze stability.

Motion Sickness in Head Mounted Displays

Theories of Motion Sickness

Sensory Conflict

MS is defined as a condition characterized by pallor, cold sweating, nausea, and vomiting that occurs as the result of the perception of certain kinds of real or apparent motion (Reason & Brand, 1975). There are many conditions that produce MS symptomology and therefore, is often named for the stimulus that produces it such as space sickness, car sickness, sea sickness, air sickness, and SS.

The sensory conflict theory, also called the sensory rearrangement theory, has been the most widely accepted theory of MS for over three decades. The basic premise of this theory as presented by Reason and Brand (1975) is as follows:

“Situations which produce motion sickness are all characterized by a condition of sensory rearrangement in which the motion information signaled by the vestibular receptors, the eyes, and the non-vestibular proprioceptors, is at variance with the kinds of inputs that are expected on the basis of past experience (p. 25).”

In other words MS arises as the result of conflicting motion information presented to the various sensory systems, particularly visual and vestibular systems. Reason and Brand (1975) identify two kinds of sensory rearrangements that they implicate in the occurrence

of MS. The first is inter-modality conflict, e.g., between the eyes and vestibular receptors, which results from three distinct conflicts. Type I occurs when the visual system signals motion while the vestibular system signals uncorrelated or incompatible motion, Type II occurs when motion is perceived in large portions of the visual field without normal associated vestibular cues, and Type III is when the vestibular system is receiving a proper stimulus in the absence of expected visual signals. Examples of events that trigger inter-modality conflict might be reading while traveling in a car or operating a fixed-base simulator with a moving display. The second is intra-modality or intra-labyrinthine, which is the result of conflict between the semicircular canals and the otoliths. There are also three distinct types of intra-modality conflicts. Type I occurs when the semicircular canals and otoliths signal contradictory information, Type II occurs when the semicircular canals signal in absence of correlated otolith signals. Type III occurs when otolith signals occur in absence of correlated semicircular canal signals. Examples of situations that might cause intra-modality conflict are low frequency oscillations, weightless flight, or rotation about an off-vertical axis.

A variation of the sensory conflict theory is the subjective vertical theory (Bles, Bos, de Graf, Groen, & Wertheim, 1998). The basis of this theory lies in the observation that MS only occurs when there is a real or apparent change in gravity with respect to the head. Bles et al. (1998) explained that all situations that provoke MS involve a variance or rearrangement between the sensed vertical, which is determined by integrated information from the eyes, vestibular system, and non-vestibular proprioceptors, and the expected or subjective vertical.

Sensory conflict theory offers little explanation of why sensory conflict results in MS. Treisman (1977) presented a view which explains MS as an evolutionary development. Sometimes referred to as the toxin defense theory, Treisman proposes that MS acts similarly to an early warning system for detecting the effects of a neurotoxin. The theory suggests that MS is an appropriate adaptive response to inappropriate stimulus. This theory states that MS is generated by situations that produce continuous challenges to maintaining the alignment between the two spatial reference systems that result in neural stimulation similar to those of poisoning.

Although there are theories of MS that share some characteristics with the sensory conflict theory, there are also other unique theories of MS. There are two specific alternatives to the sensory conflict theory, particularly the eye movement/nystagmus theory of MS as proposed by Ebenholtz (1992) and the postural instability/ecological theory of MS from Riccio and Stoffregen, (1991) that are particularly relevant to the case of HMD VEs.

Eye Movement Theory

The eye movement theory of MS, unlike the sensory conflict theory, is focused on sustained reflexive eye movements as the precipitator of MS (Ebenholtz, 1992; Sheldon, Ebenholtz, Malcolm, Cohen, & Linder, 1994). Specifically, Sheldon et al. (1994) proposed that:

“Given the close association between vestibular and oculomotor activity, we 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).”

This theory proposes that the reason labyrinthine-defective individuals don't experience MS is because they lack vestibular nystagmus and other vestibulo-ocular reflexes. The major criticism of this theory is that it doesn't account for the fact that blind people experience MS.

Postural Instability Theory

Another popular theory of MS is the postural instability theory (Riccio & Stoffregon, 1991) that has its roots in ecological psychology. This theory proposes that MS is caused by prolonged periods of instability of postural control. Riccio and Stoffregon (1991) state that “detection of prolonged instability is both a necessary and sufficient condition for MS. That is, animals will become sick if and only if it picks up information about prolonged postural instability (p. 218-219).” According to this theory, MS symptoms will lessen when the organism allows their posture to do what the environment affords. An argument against postural stability theory is MS occurs in posturally neutral environments (Moss, 2008). Although Riccio and Stoffregon (1991) propose that MS cannot be induced in conditions of full passive restraint, Warwick-Evans, Symons, Fitch, and Burrows (1998) found no difference in MS symptoms between conditions with or without restraint.

Simulator Sickness and Specific Factors in Head Mounted Displays

Simulator Sickness

SS is a subset of MS that occurs in synthetic environments. SS has been observed in a wide variety of VEs including HMD units. Since HMDs are primarily visual in nature, SS is thought to be visually induced. SS falls under the larger topical area of visually induced motion sickness (VIMS). Hettinger and Riccio (1992) state the following regarding VIMS:

“VIMS appears to occur most frequently in two general situations: (1) when perceivable and excessive lags are present between head movements and recomputation of the visual display when using HMDs, and (2) when observers view visual representations of self-motion that produce strong experiences of self-motion in the absence of actual physical displacement (i.e., when a large portion of the visual field is in motion but the observer is not) (p. 306).”

Hettinger, Berbaum, Kennedy, Dunlap, and Nolan (1990) state that “SS closely resembles true MS (i.e., sea or air sickness) but is generally less severe (p. 171).”

Blade and Padgett (2002) defined SS as:

“Various disturbances, ranging in degree from a feeling of unpleasantness, disorientation, and headaches to extreme nausea, caused by various aspects of a synthetic experience. Possible factors include sensory distortions such as abnormal movement of arms and heads because of the weight of equipment, long delays or lags in feedback, and missing visual cues from convergence and accommodation (p. 23).”

Kennedy, Lane, Berbaum, & Lilenthal (1993) indicated that SS occurs as a result of elements of the visual display and visuo-vestibular interaction, which are common for inducing MS. Hettinger et al. (1990) stated that “disturbances of the oculomotor system (e.g., asthenopia) are more prevalent in this disorder than in other forms of MS (p. 172).” Asthenopia refers to symptoms such as eyestrain, headache, and blurred vision that are often associated with SS, but are not typically associated with MS.

Kennedy, Lane, Berbaum, & Lilenthal (1993) identified three clusters in which symptoms of SS fall. These symptom clusters are disorientation, nausea, and oculomotor. These symptoms have been found to vary in magnitude depending on the situation, such as in a VE, a simulator, or on a ship or plane (Lawson et al., 2002). Draper et al. (2001) indicated that the occurrence and severity of SS is influenced by past experience with simulated environments, exposure time, and individual factors, with SS less likely to occur in those with previous experience with simulated environments. As SS occurs in many different VEs used for training, SS can have a profoundly negative impact on the transfer of skills learned in training situations (Hettinger et al., 1990).

Previous literature has indicated multiple possible causes of SS such as latency (Wildzunus, Barron, & Wiley, 1996; DiZio & Lackner, 1997; Jennings, Craig, Reid, & Kruk, 2000; Jennings, Reid, Craig, & Kruk, 2004), FOV (DiZio and Lackner, 1997), image scale factor (Draper et al., 2001), and occlusion of peripheral vision (Moss & Muth, 2011). Latency has received the most attention and although many researchers have presented findings that indicate latency to be the problem, other researchers have not been able to confirm those findings (Draper et al., 2001; Moss and Muth, 2011).

There are also other unexplored causes of SS such as the frequency and amplitude of latency in an HMD. Golding et al., (2001) presented evidence to support the idea that low frequency horizontal oscillations can cause MS symptoms and Wu et al. (2011) found that these low frequency oscillations occur in the visual scenes of HMD systems with head trackers such as the one used in DiZio and Lackner (1997).

Vection

VE simulations as they exist today can often produce illusory self-motion often referred to as vection. Vection has been identified as a possible cause of MS (Reason & Brand, 1975; Flanagan, May, & Dobie, 2004) and SS (Hettinger et al., 1990). Aside from MS, illusory self-motion has been shown to cause pronounced postural adjustments and/or a sense of disequilibrium in the observer (Hettinger, 2002). Although vection is often used to describe illusory self-motion phenomena induced by a dynamic, large field-of-view optic flow patterns, it can also describe illusory self-motion when there is a relatively small field-of-view. Factors of the visual display that affect vection are field-of-view size, temporal and spatial frequency of the visual scene, and the presence of background and foreground information. Hettinger (2002) states “vection can be induced across all six degrees of freedom of body motion (e.g., roll, pitch, yaw, and linear translations) and may be experienced as rotational motion, linear motion, or some combination of the two (p. 475).”

Many studies have been performed to establish the relationship between vection and MS using an optokinetic drum stimulus. Stern, Hu, Anderson, Leibowitz, and Koch

(1990) exposed participants to an optokinetic drum with one of three conditions. The conditions were either unobstructed full visual field condition, which was the control, a restricted visual field condition, or a fixation condition. After exposure to the rotation participants in the control condition reported significantly higher levels of vection and MS symptoms. Hu et al. (1997) explored the relationship between the spatial frequency of vertical stripes in a rotating drum on vection-induced MS. Participants were exposed to 6, 12, 24, 48, or 96 rotating vertical black and white stripes. They observed the highest vection ratings and highest frequency of nystagmus eye movements in the condition with 24 stripes. In the same condition participants also experienced the most severe symptoms of MS and abnormal gastric tachyarrhythmia. Hu et al. (1997) suggest “the level of vection ratings reflect the sensory mismatch between the visual and vestibular systems while viewing an optokinetic rotating drum (p. 310).” Hu and Stern (1998) explored the relationship between optokinetic nystagmus and vection-induced MS by exposing participants to a rotating drum with vertically striped walls. The participants were asked to focus on the rotating stripes rather than letting them blur before their eyes. They found that horizontal eye movements were positively related to vection and scores on MS symptoms.

With the advent of VE technology the study of the relationship between vection and MS has expanded beyond the use of optokinetic drums to the use of flight and vehicular simulations as well as HMDs. Hettinger et al. (1990) assessed the relationship between vection and motion sickness by exposing participants to 15-min. computer generated flight scenarios with repeated turns, banks, and changes in apparent altitude.

The participants reported their experience of vection and MS. They found that participants who experienced vection reported significantly higher rates of sickness. Flanagan et al. (2004) also examined the relationship between vection and MS. They exposed participants to both static and moving visual scenes. They found that the participants experienced significantly higher levels of MS in the moving visual scene condition. Although many studies identify a link between the experience of MS symptomology and vection, there are others that don't support this connection. For instance, Webb and Griffin (2003) did not find a correlation between vection and MS in the peripheral vision or foveal vision conditions. In addition, there was no significant difference between MS in the conditions. They did find that vection was significantly greater in the peripheral vision condition as opposed to the foveal vision condition.

Latency

Latency in HMD VEs refers to the time between a head movement and change in the depiction of the environment in the visual display. Latency is associated with the computational processes to compensate for actions triggered by the user. These include processing information from the user's tracking device, resultant computations, and the display of results (Bryson, 2002). System latency is typically increased in VE systems with an emphasis on pictorial fidelity. The higher fidelity the images in the displays become, the more system latency is present. Hettinger and Riccio (1992) state "enhanced pictorial realism in HMDs contributes directly to the computational demands placed on the system, thereby contributing directly to the presence of lags that are likely to

exacerbate VIMS (p. 307).” According to Kaber, Draper, and Usher (2002) latency has two common sources, stating that “latency often occurs when the computer system cannot update a virtual world quickly enough, and communication delays can be present between the remote world and the local controls and displays (p. 396).” These communication delays are the result of separate components in the HMD system from sensor to actuator, which operate using their own clocks, such as cameras, orientation sensors, displays and motors (Wu et al., 2011). See Figure 2.2.

Figure 2.2. Typical configuration with components operating on independent clocks causing non-constant latency in the system (From Wu et al., 2011).

Multiple studies have found a relationship between latency and SS (Wildzunas, Barron, & Wiley, 1996; DiZio & Lackner, 1997; Jennings, Craig, Reid, & Kruk, 2000; Jennings, Reid, Craig, & Kruk, 2004) while others have found no relationship when latency was manipulated in the absence of a head tracking sensor (Moss and Muth, 2011). Wildzunas et al. (1996) had 10 aviators fly missions using a flight simulator. The aviators were exposed to added latency of 67, 133, 267, 400, and 533 ms on top of

the inherent system latency of 116 ms. Their results suggested that latency greater than 267 ms were most perceptible to the aviators while the 533 ms latency condition was the only condition with a significant increase in MS symptoms. DiZio and Lackner (1997) had 21 participants wear an HMD and make head movements with latency of 67 ms or the latency inherent in the system, 100 ms, 200 ms, and 300 ms of latency. Participants made 24 head movements of 12° to 180° over two minute intervals. They repeated the sequence five times with one minute breaks between. Participants experienced significant sickness in all latency conditions and significant increases in sickness as the latency increased. Six of their 21 participants withdrew before completion of the study. They also found that decreasing the FOV in the HMD greatly reduced sickness. Jennings et al. (2000) and Jennings et al. (2004) conducted similar experiments to determine the relationship between latency and SS. Participants in both studies consisted of two qualified experimental test pilots and one line pilot. They had participants perform a hovering task in a simulator. The pilots wore an HMD that presented the external imagery and flight symbology. There were latency conditions of 67, 134, 184, and 334 ms added to the displays. Jennings et al. (2004) also added control latency of 85, 162, 212, and 362 ms. In both studies, multiple pilots experienced MS symptoms such as eyestrain, vertigo, dizziness, and nausea with an increase in symptoms as latency increased. Symptoms were most frequently reported at the 184 ms latency condition. Jennings et al. (2000) explains their overall findings regarding MS symptoms by stating:

“One can say that frequency and amplitude of symptoms tend to increase with amplitude of the disparity between and among sensory/perceptual modalities.

Increasing visual lag clearly increases perceptual disparity vis-à-vis the vestibular and proprioceptive systems in the simulator tasks employed in this study (p. 3-71).”

Jennings et al. (2004) did not find any relationship between control latency and MS symptoms. As a result of their study Jennings et al. (2000) proposes that inappropriate visual latency in advanced cockpit devices could cause onset of MS and these symptoms may cause the pilot to lose control of the aircraft if they are severe.

Unlike studies using head trackers, Moss and Muth (2011) used an HMD with a camera mounted on top as the sensor. The camera captured images from a real world laboratory environment and participants were tasked with locating objects around the laboratory. This task was performed over the course of 5 experimental trials and participants’ experience of SS was measured between each trial. Participants were exposed to either 0 ms added latency or 200 ms added latency. Unlike previous studies using head trackers as the sensor, Moss and Muth found no significant difference in SS as the result of exposure to added latency. This finding did not support prior research, in which latency was the cause of SS, indicating that something more than addition latency may be affecting participant SS.

Frequency and Amplitude of Latency

Recent work by Wu et al. (2011) measured end-to-end latency (i.e., sensor to actuator) in two systems. The first system used a camera as a sensor and a computer monitor as the actuator. This set up was similar to the HMD set up used by Moss and

Muth (2011) that found no effect for latency on SS. Wu et al. (2011) moved a black bar across a white background for the camera to sense. See Figure 2.3 and 2.4. The latency was measured between the sensing of this event and its actuation on the computer monitor. Figure 2.5 depicts what is seen by an outside observer when the sensed input (lower section) and the actuated output (upper section) occur. The image tear in the actuated output is due to the image being redrawn on the LCD monitor. Over multiple trials they found that neither sensing nor actuation happened instantaneously and latency is not constant, but instead varies. In the camera system they found that latency varies at a 17 Hz oscillation with 10-20 ms of amplitude. See Figure 2.6.

Figure 2.3. Camera-to-monitor system (From Wu et al., 2011).

Figure 2.4. Black bar with white background for camera-to-monitor system (Wu et al., 2011).

Figure 2.5. Camera-to-monitor system as seen by outside observer (From Wu et al., 2011).

Figure 2.6. Relationship between sensed input and actuated output in camera sensor system (From Wu et al., 2011).

The second system utilized an orientation sensor as the sensor and a motor for actuation. See Figures 2.7 and 2.8. This system was similar to the HMD system used by DiZio and Lackner (1997) which utilized a head tracker to sense head movements within the virtual environment. The sensor is mounted on a white background and was manually rotated. These rotational movements were processed by the computer and then turned the motor to the same orientation. Latency was measured by comparing their orientations. Unlike the camera system used, the latency distribution changed between trials. See Figure 2.9 and 2.10.

Figure 2.7. Orientation sensor-to-motor system (Wu et al., 2011).

Figure 2.8. Orientation sensor-to-motor system as seen by the outside observer (From Wu et al., 2011).

Figure 2.9. Relationship between sensed input and actuated output in orientation sensor system (From Wu et al., 2011).

Figure 2.10. Relationship between sense input and actuated output in orientation sensor system (From Wu et al., 2011).

Overall they found that there was a drift in sensor error which causes latency to change throughout each trial. In addition, this latency drift was in the range of 0.5-1.0 Hz with perceived oscillations in latency at approximately 20-100 ms.

Prior to the use of VE much MS research focused on transportation situations such as those in various land vehicles, ships (large and small), and aircraft. Much of this research has focused on vertical heave motion like that experienced on ships. Several studies have concluded motion at frequencies below 1.0 Hz have yielded the highest level of nausea (Alexander, Cotzin, Klee, & Wendt, 1947; O'Hanlon & McCauley, 1974; Lawther & Griffin, 1988; Duh, Parker, Philips, & Furness, 2004). O'Hanlon and McCauley (1974) using a motion generator to simulate vertical heave motion like that found on ships reported the region of maximum nauseogenicity to be in the range of 0.17 to roughly 0.20 Hz. See Figure 2.11.

Figure 2.11. Relationship of MS to wave frequency and average acceleration (From O'Hanlon & McCauley, 1974).

Several studies have concluded that horizontal oscillatory motion of constant peak acceleration amplitude yields increased nauseogenicity as frequency decreases in the range of 1.0 to 0.2 Hz (Golding & Markey, 1996; Golding, Finch, & Scott, 1997; Golding et al., 2001). Golding et al. (2001) subjected participants to conditions of 0.1 Hz, 0.2 Hz, and 0.4 Hz horizontal oscillation by pulling a canvas cab with a seat and headrest horizontally. They determined 0.2 Hz to be the maximum nauseogenic with the quickest onset of nausea. Above and below the 0.2 Hz condition nausea decreased and the time to nausea increased. The sensory conflict theory of MS and the subjective vertical theory of MS predict an increased nauseogenicity toward lower frequencies below 1.0 Hz. Golding et al. (2001) support this increase in nauseogenicity below 1.0 Hz, but further indicate a decline in nauseogenicity at ultra-low frequencies below 0.2 Hz. These same low frequencies of 0.5 to 1.0 Hz have been found to occur due to orientation sensing error inherent in systems using orientation sensors (Wu et al., 2011). This range is well within the region in which individuals experience MS symptoms.

Oculomotor Resting States and HMD After-Effects

Oculomotor after-effects have been associated with the use of HMDs. Previous researchers have attributed these after-effects to the violation of the vergence – accommodation relationship while in an HMD. Vergence refers to movement of the eyes to converge or diverge to allow the brain to fuse the two eyes' images as fixation distance changes. Accommodation refers to changes in optical power to bring objects into focus. Accommodation and vergence are cross-linked, meaning that when the eyes converge on

an object they also focus on that object and vice versa. Wann, Rushton, & Mon-Williams (1995) stated that:

“Under normal viewing conditions, accommodation and vergence eye movements vary synchronously and are dependent on object distance. In contrast, within a VE system the eyes must maintain accommodation on the fixed LCD screens, despite the presence of disparity cues that necessitate vergence eye movements in the virtual scene. The computer generated optic array lacks the blur cues that arise in natural vision, and the focal characteristics of the display are closer to those of a pictorial representation. The possibility of producing a relative prismatic effect through decentration of the viewing optics is common to both binocular and stereoscopic HMDs (p. 2731).”

The displays in an HMD do not provide the same visual cues as does a normal viewing situation. Exposure to non-standard visual cues in an HMD challenge the visual system and can result in HMD related oculomotor after-effects. After-effects can also be attributed to distance of the displays from one another. For instance, displays set too close together force the eyes into prolonged convergent positions which result in inward shifts in dark vergence posture whereas if the displays are set too far apart the eyes are forced into prolonged divergent positions which result in outward shifts in dark vergence posture (Wann & Mon-Williams, 2002).

Dark Vergence Posture

Eye movements discussed earlier were primarily conjunctive movements, whereas vergence (convergence/divergence) is a disjunctive eye movement, meaning that the eyes move in opposite directions. Specifically, vergence is the movement of the eyes in opposite directions to maintain binocular fusion. Vergence is used to view objects in space. Eye movements such as accommodation, which will be discussed below, and vergence have resting states when the viewer is not fixating on objects in space. The vergence resting state is referred to as dark vergence posture and is the distance at which the two eyes converge in darkness; it is thought to be a measure of the tonic innervation to the extraocular rectus muscles..

The removal of disparity information can act to open the normal vergence feedback loop. This open-loop vergence bias is known as heterophoria. Wann and Mon-Williams (2002) describe heterophoria as a “slight deviation from perfect binocular positioning that is apparent when the eyes are dissociated (p. 739).” Heterophoria can be esophoric when the visual axes are convergent and exophoric when the visual axes are divergent (see Figure 2.12).

Mon-Williams, Wann, and Rushton (1993) noted that HMDs could cause binocular deficits such as heterophoria. In their experiment participants donned an HMD that allowed them to view a computer generated VE of an illusory road network which participants were asked to “bike” through. They found a significant esophoric shift among participants. Mon-Williams, Plogy, Burgess-Limerick, and Wann (1998) reported that the occurrence of heterophoric shifts in VE systems is the result of a disruption of the

cross-link between accommodation and vergence. In addition, if users of bi-ocular HMDs do not look through the center of the displays or if the displays are not properly aligned to match the users' interpupillary distance (IPD), the demands on the vergence system will cause changes in heterophoria. Mon-Williams and Wann (1998) attempted to observe heterophoric shifts in participants using field-sequential shutter glasses to present 3D scenes as opposed to an HMD. Participants viewed a variety of conditions such as the presentation of stereoscopic photographs, a game task where they were required to scan and attend to display details, and another condition where they viewed a cross that oscillated from infinity to 40 cm in a sinusoidal fashion. There were no significant differences in heterophoria after immersion although multiple participants were found to have significant clinical changes in heterophoria, primarily in the form of esophoric shifts and predominately in the conditions that employed the oscillating cross. Contributors to heterophoric shifts might be poor illumination, poor contrast, and close working distances (Wann, Rushton, & Mon-Williams, 1995).

Figure 2.12. Examples of heterophoric shifts in binocular vision (From Wann & Mon-Williams, 2002).

Howarth and Costello (1997) indicated that heterophoric shifts in response to HMD use are likely to increase sore and aching eyes. Past research on the relationship between HMD use and the vergence system has focused on changes to the vergence system, but little research has examined the link between changes to the vergence system as the result of HMD use and its relationship to the occurrence of SS. Multiple studies explore the oculomotor after-effects of HMD use, but relatively unexplored is the relationship between oculomotor after-effects as the result of HMD use and the experience of SS. Two particular studies examined the relationship between dark

vergence shifts and SS as the result of HMD use. First, St. Pierre, Salley, Muth, and Moss (2011a) used an identical experimental procedure to that of Moss and Muth (2011), but in addition measured dark vergence posture of participants before and after HMD use. A significant inward shift in dark vergence posture was found after HMD exposure. However, no relationship was found between the shift in dark vergence posture and SS. Although this study found a shift in dark vergence posture from pre to post, the researchers didn't set the distance between the HMD displays to match the interpupillary distance (IPD) of the participant. St. Pierre, Tyrrell, and Muth (2011b) used the same experiment, but measured participant IPD using an auto-refractometer. The displays of the HMD were set according to the IPD of each participant. No significant shift in dark vergence posture was found from the use of an HMD. However, dark vergence posture prior to HMD use was correlated with SS among the sickest half of participants. Both studies had small sample sizes ($N = 20$) so it's unclear whether similar findings would be present with a larger sample, but it is clear that the visual nature of an HMD shares a relationship to SS.

Dark Focus

Another oculomotor factor important in viewing objects is accommodation. Accommodation is the change in optical power needed to maintain focus on an object as its viewing distance changes and is measured in diopters (D). Much like vergence, accommodation also has a resting (tonic) state called dark focus. Dark focus can be

understood as the distance at which the accommodative system views in the absence of visual stimulation (in the dark).

Oculomotor after-effects in VEs have primarily been studied with regard to the vergence system. However, after-effects have also been found in the accommodative system. Evidence supporting the relationship between SS and dark focus in VE technology is sparse. Fowkles, Kennedy, Hettinger, and Harm (1993) performed a series of experiments to explore the relationship between dark focus and SS using a moving-base helicopter flight simulator with CRT visual systems. They also explored the role of the autonomic nervous system in dark focus of accommodation. Their results suggested that in situations with low stress and minimal focal demands, an inward shift in dark focus was observed among sick participants. When demands were high with increased sympathetic nervous system activity, participants who were sick experienced an outward shift in dark focus. Although Fowkles et al. (1993) found significant shifts in dark focus, their dark focus measures were taken in a "nearly light tight room (p. 613)." For accurate dark focus measurements the measurements must be taken in a light tight room. The measurements in this experiment could have been altered by the presences of low levels of light. St. Pierre et al., (2011) examined the relationship between dark focus and SS after the use of an HMD. A negative correlation was found between dark focus in the left eye prior to HMD use and participant reports of sweating. In addition, a positive correlation was found between dark focus in the left eye after HMD use and participant reports of the experience of vertigo.

According to Rushton and Riddell (1999) there is disagreement in the literature about the effects of bi-ocular viewing on oculomotor variables. Kotulak and Morse (1995) presented participants with both symbols and a visual scene with real objects. The participants switched their focus between the real objects and the symbols in the visual scene. The authors found that aviators accommodated to a significantly nearer position when the HMD focus was fixed at 0.0 D, when they attended to symbols rather than the visual scene, and when the aircraft was in motion rather than stationary. On the other hand, Rushton, Mon-Williams, and Wann (1994) required participants to scan and attend to display details during the presentation of a game task in the HMD. The authors found no significant shifts in accommodation. Rushton and Riddell (1999) state that the “superior quality of the display in the Kotulak and Morse study would provide a better stimulus to accommodation (p. 73).”

Present Study

The primary goal of the current study was to examine the relationship between varying system latency in HMDs and the experience of SS. A secondary goal of this study was to determine if a relationship exists between the experience of SS and oculomotor resting states. The purpose of this research was to expand the current body of SS literature by examining factors that have yet to be studied and controlled in HMD research. This study explored factors not researched in HMDs before to examine if they are linked to the experience of sickness in HMD VE.

This research was motivated by several studies. Studies regarding adding latency to the HMD VE by DiZio and Lackner (1997) and Moss and Muth (2011) have yielded conflicting results as to the relationship between latency and SS. Among the differences in these studies were the scene presented to participants and the use of head tracking. DiZio and Lackner (1997) presented a head tracked computer generated scene finding a significant relationship between sickness and latency whereas Moss and Muth (2011) presented a non-head-tracked real world scene in an HMD and found no significant relationship between sickness and latency in participants. The conflicting results of these two studies regarding latency in an HMD may indicate that there is more at play where SS is concerned than simply adding latency to the HMD VE. The factor that may be at play is the change in latency over time.

The manipulation of frequency of latency was motivated by research by Wu et al. (2011) and Golding et al. (2001). Research by Wu et al. (2011) found frequency variability in the system from sensor to actuator due to sensor error (e.g., head tracker error). They found that the inherent frequency variability caused by a sensing error to lie between 0.5 and 1.0 Hz, which as discussed above is in the range that is associated with the experience of MS. Golding et al. (2001) found that at 0.2 Hz individuals experience a maximum level of nauseogenicity during horizontal oscillation. This has prompted the question “is the result of the sensing error on the perception of the visual scene the reason people experience SS in HMDs?” Amplitude, which will manifest itself as variable latency, was also manipulated in the current study, but there was little to no research regarding amplitude and SS other than fixed manipulations in system latency.

Previous researchers thought of latency as a constant. However, it is now known that latency is variable. Latency can be either inherent to the system, referred to as base system latency, or a combination of latency added to the system and inherent latency. According to the findings in Wu et al. (2011), previous HMD research with latency utilizing head trackers as sensors, amplitude of latency should have had a variable magnitude from 20 - 100 ms. In addition to this amplitude, low frequency oscillations in latency were also present. In other words, previous work that employed a head tracking sensor may have been manipulating both amplitude and frequency of latency unknowingly. These inadvertent manipulations may have had an effect on SS in the user, but not been due to the proposed added latency.

The idea that latency varies over time may help explain the conflicting findings in previous research on the relationship between latency and SS. For instance, DiZio and Lackner (1997) used a system that utilized a head tracker, which would introduce sensing error between 0.5 and 1.0 Hz (Wu et al., 2011), and they found that latency increased SS, but failed to account for the amplitude and frequency of latency. This is in contrast to Moss and Muth (2011) who utilized a system with a camera mounted on the HMD to capture real world images. This system lacked the sensing errors that produce low frequency oscillations, thus eliminating their influence and finding no effect of latency on SS.

This current study was a between-subjects design consisting of four conditions (see Table 3.1). The independent variables were added latency, and frequency and amplitude of latency. Levels of added latency were ~0 ms and ~200 ms. Levels of

frequency of latency were either 0 Hz or 0.2 Hz. Levels of amplitude of latency were either fixed or variable at 0-200 ms. Multiple dependent variables were measured in the current study. SS was measured using the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993) and MS was measured using the Motion Sickness Assessment Questionnaire (MSAQ; Gianaros, Muth, Mordkoff, Levine, and Stern, 2001). In addition, dark vergence was measured by the Vergamatic II, and a measure of dark focus by the Grand Seiko Co., LTD WV-500 Auto-Refractometer.

Hypotheses

It was further hypothesized that added latency would yield higher SS levels than no added latency. There is a conflict in the literature regarding whether or not latency has an effect on SS levels. According to multiple research studies (Wildzunas et al., 1996; DiZio & Lackner, 1997; Jennings et al., 2000; Jennings et al., 2004) added latency increases sickness whereas other studies (Moss & Muth, 2011; Draper et al., 2001) have failed to confirm the relationship between added latency and sickness. Controlling the amplitude and frequency of latency will allow for an accurate assessment of the relationship between added latency and SS. It was hypothesized that variable amplitude of latency would yield higher SS levels than fixed amplitude. There is no literature that studies this directly in an HMD. However, past studies that used HMDs with head trackers may have introduced varying amplitude of latency due to sensing errors. These errors would have added variability in latency that the researchers would not have controlled for. This could be an explanation for why DiZio and Lackner (1997) found an

effect for latency on SS while Moss and Muth (2011) did not. Moss and Muth used a system that did not require the use of a head tracker and hence did not have low frequency variability in latency. It is probable that the DiZio and Lackner study introduced variable amplitude from sensing error, which suggests that the amplitude had an effect on SS while latency did not.

The present study hypothesized that conditions with a frequency of latency of 0.2 Hz would yield significantly higher SS levels than conditions with a 0 Hz frequency. Although no research exists regarding manipulations of frequency of latency in an HMD VE, there is considerable research to suggest that exposure to low frequency motion between 0.1 Hz and 1.0 Hz yield increased MS compared to other frequencies of motion (Alexander et al., 1947; O'Hanlon & McCauley, 1974; Lawther & Griffin, 1988; Golding & Markey, 1996; Golding et al., 1997; Golding et al., 2001; Duh et al., 2004). Additionally, Golding et al. (2001) found the frequency of 0.2 Hz to be the zone of maximum nauseogenicity. Wu et al. (2011) found that a sensing error between 0.5 and 1.0 Hz is inherent in head tracked systems and that likely results in a perceived motion that is not related to the real motion.

No significant differences were expected in dark vergence from pre to post because the displays in the HMD were to be set according to the IPD of each participant.. Alternatively, if significant shifts in dark vergence did occur it was hypothesized that there would be a significant correlation between SS and the change in dark vergence. Based on disagreement in prior research regarding dark focus changes as the result of HMD use, it is unclear as to any changes that might occur. If shifts in dark focus did

occur, it was hypothesized that there would be a significant correlation between SS and the change in dark focus.

CHAPTER III

METHOD

Participants

One hundred twenty participants (56 male), thirty participants per condition (14 male per condition), were recruited via flyers advertising the study posted in various locations on Clemson University's campus. Participants were also recruited using the Psychology Department's subject pool through Clemson University's SONA experiment management system website. Participants responding to the on-campus flyer were paid \$10 per hour while SONA participants were given credit for participation through the SONA system for course credit in addition to \$10 per hour compensation.

Participants completed a pre-screening survey and a Motion Sickness History Questionnaire (MSHQ) to determine suitability for participation. Individuals who reported the experience of MS symptoms frequently or easily were excluded from the study as well as those who reported previous experience in VEs or HMDs. Individuals who self-reported any history of brain, heart, stomach, visual (other than corrected vision) or inner ear problems were excluded from participation. Additionally, any female self-reporting being pregnant was ineligible for participation. Individuals with corrected vision who did not have or wear contacts were ineligible to participate because the use of glasses prevents optimal HMD fit. Eligible participants were instructed to abstain from the use of alcohol, nicotine, and caffeine for 12 hours prior to their participation in the study. Participants were asked to avoid vigorous physical activity for one hour prior to

the experiment. Participants who reported feeling sick or in less than their normal physical state on the day of the experiment were rescheduled and sent home.

Design

The present study was a between-subjects design consisting of four conditions. A between-subjects design was used to prevent SS adaptation as well as to limit the dropout rate from condition to condition.

The independent variables in the current study were latency added, amplitude of latency, and frequency of latency. The independent variable of latency added consisted of two levels. The same levels were used as in Moss and Muth (2011), which were the inherent system delay or 0 ms added and 200 ms added. DiZio and Lackner (1997) also used a 200 ms condition in a study in which they found MS severity to increase monotonically with latency added.

Table 3.1. List of conditions and levels of factors.

Condition	Added Latency (ms)	Frequency (Hz)	Range of Amplitude (ms)	Base System Latency (ms)	Total Latency (ms)
Baseline	0ms	0Hz	0ms	~70ms	~70 ms
Baseline + Constant	200ms	0Hz	0ms	~70ms	~270 ms
Wave pool (fixed amplitude)	100ms	0.2Hz	100ms	~70ms	~70-270ms
Ocean (varying amplitude)	100ms	0.2Hz	20-100ms	~70ms	~70-270ms

The frequency and amplitude of latency independent variables both consisted of two levels. According to Golding et al. (2001), 0.2 Hz is the zone of maximum nauseogenicity with the quickest onset of nausea. They also found that above and below 0.2 Hz there are swift decreases in nausea. The amplitude of latency manipulation manifested itself in the form of changing latency. Essentially amplitude of latency only had two levels in that it is either fixed at 100 ms or varying amplitude with a range of 20-100 ms. The fixed amplitude condition or wave pool condition was considered to be a sine wave with a fixed amplitude. The varying amplitude condition or ocean condition was considered to be when the sine wave amplitude changed every cycle. The amplitude from the wave pool condition (fixed amplitude) can be seen in Figure 3.1 and amplitude from the ocean condition (varying amplitude) can be seen in Figure 3.2. There was little to no background regarding effect of amplitude manipulation in HMD VEs or VEs in general so little is known regarding ideal manipulations. Since it will manifest itself in the form of changing latency, the manipulations resembled those of the latency added conditions. The wave pool and ocean conditions both contain manipulations of amplitude of latency with a frequency of 0.2 Hz. It is important to note that frequency and amplitude of latency are independent only when each are a non zero. When one is zero, the other must be zero. Alternatively, if one is a non zero, the other must also be a non zero.

Figure 3.1. Fixed amplitude of 100 ms in the wave pool condition.

Figure 3.2. Varying amplitude of 20-100 ms in the ocean condition.

Dependent variables in this experiment were measures of SS as measured by the SSQ (Kennedy et al., 1993), a measure of motion sickness provided by the MSAQ (Gianaros et al., 2001), dark vergence measured by the Vergamatic II, and a measure of dark focus by the Grand Seiko Co., LTD WV-500 Auto-Refractometer.

Previous research in the lab regarding latency and SS (Moss et al., 2008) yielded an $f^2 = 0.64$ which indicated that the current study required approximately 19 participants per condition. Another previous study in the lab regarding the change from pre to post regarding dark vergence (St. Pierre, Salley, Muth, & Moss, 2011) yielded an $f^2 = 0.32$ which indicated that the current study required approximately 31 participants per condition.

A study regarding pre to post changes in dark focus (Fowlkes et al., 1993) yielded an $f^2 = 0.93$. This suggested the need for approximately 11 participants per condition. Correlational data from the same experiment regarding the relationship between dark focus and SS yielded an $f^2 = 0.69$, which suggested a need for approximately 18 participants per condition.

A study regarding the relationship between frequency and sickness (Golding et al., 2001) yielded an $f^2 = 0.31$. This suggested the need for approximately 32 participants condition. No studies of amplitude variability in the form of varying latency are available to determine an appropriate sample size for the current study.

All sample size estimates were based on the following equations:

$$N = \frac{L}{f^2} \quad (1)$$

$$f^2 = \frac{r^2}{1-r^2} \quad (2)$$

$$r^2 = \frac{t^2}{t^2 + df} \quad (3)$$

$$f^2 = (F * df_{numerator}) / df_{denominator} \quad (4)$$

$$df_{numerator} = k - 1 \quad (5)$$

$$df_{denominator} = N - k \quad (6)$$

Equations 1 thru 4 and the table for determining L values can be found in Cohen, Cohen, West, and Aiken (2003). Equations 5 and 6 were taken from Jackson (2009). It was determined that 120 participants (30 per condition) would be necessary for the current study. This number was selected because it provided more than adequate power for each analyses in the current study.

Participants were randomly assigned to one of four conditions based on numbers calculated using a random number generator. The expectation was that more female participants than male participants would be available for the experiment due to enrollment in psychology courses at Clemson University. Due to this disparity, care was taken to ensure that there was a similar distribution of male and female participants in each condition.

This study was approved by the Clemson University Institutional Review Board. Participants completed the approved consent form prior to participations which outlines the background, potential benefits and risks, and procedure of the experiment. Participants were also informed of their right to discontinue participation at any time without penalty.

Materials and Apparatus

The Clemson University Institutional Review Board approved consent form, a demographic questionnaire, and the MSHQ (From Reason, 1968, as cited in Reason & Brand, 1975) were distributed to participants prior to the experiment. The SSQ and MSAQ were administered during the experimental sessions as measures of SS and MS. Dark vergence measurements were taken using the Vergamatic II and dark focus measurements were taken using Grand Seiko Co., LTD WV-500 Auto-Refractometer, both provided by Dr. Richard Tyrrell and his Visual Perception and Performance Laboratory. Other materials were provided by Dr. Eric Muth and his Applied Psychophysiology Laboratory at Clemson University. These items include an HMD, video camera, camera lens, and eye-cups. The manipulation of system latency was made possible by an in-house program developed by Salil Banerjee, a graduate student in the Electrical and Computer Engineering Department at Clemson University.

Head-Mounted Display (HMD)

A Kaiser Electro-Optics, Inc., *ProView™ XL 50* HMD was used in this study. Eye cups specifically for use with the *XL 50* HMD were used. A picture of the HMD with eye cups can be seen in Figure 3.3. The eye cups were of a rubber-like molding and were used to occlude external light from the environment. Since the camera on the HMD is mounted several inches higher than the actual display, the external environment needed to be occluded to eliminate any disparity between the height of the real world

environment and the environment presented in the HMD displays. The HMD displays were adjusted to match the interpupillary distance (IPD) measurement of each participant.

The HMD resolution was 1024 X 768 at a frame rate of 60 Hz. The HMD is used as a bi-ocular HMD in this study presenting monoscopic imagery. The *XL 50* HMD had the capability to be used as a binocular HMD with presenting stereoscopic imagery as well. The *XL 50* HMD had a 50° FOV diagonally, and FOV of 30° vertically and 40° horizontally. The weight of the unit was 35 oz prior to camera mount.

Figure 3.3. Kaiser Electro-Optics, Inc., *ProView™ XL 50* HMD with mounted camera and eye cups.

Digital Camera

A Uniq *UC-610CL* color digital CCD camera was used to capture images from around the laboratory in this study. This camera was mounted atop the HMD and can be seen in Figure 3.3. A side view close up of the camera can be seen in Figure 3.4.

Camera resolution is 659 X 494 active pixels at a frame rate of 110 Hz. The camera had a lens mount platform C-mount and used a 1/3" progressive scan CCD imager with R, G, and B primary color mosaic filters. The camera weighed 200 g.

Figure 3.4. Uniq *UC-610CL* color digital camera.

A Dalsa *X64 CL Express™* PCI camera link frame grabber for image capture was installed on a Windows XP computer that contained a 3.2 Ghz *Pentium IV* processor and 2 GB of RAM. A 256 Mb *PCI Express™* video card was used. The captured images from the camera were projected on the HMD display as well as the computer monitor for the experimenter to observe.

Update Delay Program

The manipulation of system latency was made possible by an in-house program developed by Salil Banerjee, a graduate student in the Electrical and Computer Engineering Department at Clemson University. The programming library for image acquisition and control used to develop the software was Dalsa's *SaperaTM LT*, which is based on a set of C++ classes. The following description of how the program provided additional latency to the system was provided via personal communication from former graduate student, Tom Epton, in the Electrical and Computer Engineering Department at Clemson University, which can be found in Moss (2008).

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 the camera operates at half of the normal rate to closely match the display rate which operates at 60 Hz.

After writing the update delay program, the inherent system latency and added system latency as well as amplitude and frequency of latency were measured. This was necessary to confirm that the program operated as proposed. This was done by using the methodology employed in system#1 in Wu et al. (2011), pictured in Figure 3.5.

Figure 3.5. Experimental setup to determine inherent system latency in the HMD.

To determine the latency as well as amplitude and frequency of latency, a long black vertical stripe was moved horizontally from the right vertical stripe to the left vertical stripe, this is referred to as the “event.” The Uniq *UC-610CL* color digital camera that is typically mounted atop the HMD was mounted on a tripod (pictured in the

bottom center of Figure 3.5) in front of the event. The HMD was suspended vertically (pictured in the top right hand portion of Figure 3.5). In front of the HMD displays is a Fastec Trouble Shooter 1000 high speed camera, which was mounted on a tripod (pictured in the center right portion of Figure 3.5). The Fastec Trouble Shooter 1000 captured video at 480×640 resolution at up to 1,000 Hz for 4.4 seconds. It was mounted in the position to capture the real event and the actuated event in the left HMD display. This way the image of the event in the HMD display could be compared side-by-side to the real event to determine the inherent system latency from sense to actuation in the HMD by counting frames elapsed between the two images when the first image crossed a threshold relative to when the second image crossed a threshold.

To confirm the amplitude and frequency of latency was operating as intended for the proposed conditions, ten recordings were collected for five separate conditions (i.e., baseline, baseline + 200 ms, wave pool with 30 ms amplitude, wave pool with 60 ms amplitude, and wave pool with 100 ms amplitude) using the above described method. All wave pool conditions operated at a frequency of 0.2 Hz. These recordings, when analyzed, confirmed that the added latency as well as the amplitude and frequency of latency were operating as proposed.

Vergamatic II

Automated measures of binocular vergence posture were gathered using the Vergamatic II. See Figure 3.6 for picture of the Vergamatic II. This device utilized vernier alignment of dichoptically presented light emitting diode (LED) stimulus. The

measurement stimulus was presented through the use of two LED arrays. The horizontal array consisted of 128 yellow LEDs while the vertical array consisted of only two rectangular green LEDs. The vertical array was bisected by the horizontal array. Both arrays were filtered through linear polarizers. When participants viewed the arrays through the cross-polarized glasses provided, the stimulus was dichoptically presented. Through these glasses the participant saw the vertical array with the left eye and the horizontal array with the right eye. The device was programmed with a modified binary search algorithm (MOBS; Tyrrell & Owens, 1988) to guide the alignment process. The MOBS method used binary subjective responses (e.g., left/right) of evaluating psychophysical thresholds. In the case of the Vergamatic II, stimulus was presented along both LED arrays. The participant used a response box with a right button and a left button. The participant selected the right button if the horizontal array flashed a yellow light to the right of the green vertical flashing light. The participant selected the left button if the horizontal array flashed a yellow light to the left of the green vertical flashing light. With each response by the participant the MOBS algorithm restricted the range of the flashing lights to derive a measurement of a vergence posture for the participant. A host computer was used to configure the unit's operating parameters and to initiate and display the measurements.

Figure 3.6. Vergamatic II.

The physical set up, not including the Vergamatic II, consisted of a steel frame, front surface mirror, felt square, and head stabilizer with chin and forehead rests. See Figure 3.6 for setup. At the top of the steel frame were two planks of wood with a horizontal space between them. The Vergamatic II was located on top of these planks with the LED arrays projecting downward through the space between the planks. The light from the LED arrays projected downward reflecting on a front surface mirror which reflected the light toward the eyes of the participant. A front surface mirror was used so the participant did not see a double image as would occur with a regular household mirror. The head stabilizer was aligned so the light from the vertical green LED array was reflected to the left eye of the participant. The head stabilizer was in place to prevent excessive head movements that may interfere with accurate measurements. A square felt

piece hung from a wood plank at the top of the frame. This piece was used to prevent participants from seeing the light projected from the Vergamatic II directly.

Figure 3.7. Vergamatic II setup with front surface mirror, steel frame, felt square, and head stabilizer.

Auto Refractometer

The Grand Seiko Co., LTD WV-500 Auto-Refractometer was used to gather accommodative data as well as to acquire an accurate measure of IPD. Auto-refractors are modern optometric tools used for objective assessments of refractive error in patients and are often used in research to measure various aspects of accommodative response

(Mallen, Wolffsohn, Gilmartin, & Tsujimura, 2001). Like other Grand Seiko autorefractors, the WV-500 is an open-field binocular device that allows for dynamic recording of refraction and pupil size. The WV-500 calculates refractive error in two stages. Mallen et al. (2001) states

A ring target of infra-red is imaged after reflection off the retina. On the initial measurement, a lens is rapidly moved on a motorized track to place the ring approximately in focus. The image of the ring target is then analyzed digitally (p. 102).

WV-500 design and components can be seen in figure 3.8. The refractive error is measured on meridians. Static measurements of refractive error in the range of ± 22.00 D sphere, ± 10 D cylinder in steps of 0.125 D and 1° for the cylindrical axis. The WV-500 displays refractive data on a small built-in VDT as well as in hard copy output form via a built-in thermal printer.

Figure 3.8. Optical layout and external view of the Grand Seiko CO., LTD WV-500 Auto-Refractometer. Key: 1. semi-silvered mirror; 2. view window lens; 3. semi-silvered viewing mirror; 4. perforated mirror; 5. masks; 6. lens; 7. infra-red light source for measuring; 8. relay lenses; 9. mirror; 10. focusing lenses; 11. field lens; 12. aperture; 13. CCD sensor; 14. illuminating/alignment light sources; 15. fixation target; 16. forehead rest; 17. chin rest; 18. power and external interface connectors; 19. CRT monitor/alignment screen; 20. thermal printer; 21. joystick; 22. measurement start switch; 23. anti-sliding screw lock. (From Mallen et al., 2001).

Motion Sickness History Questionnaire (MSHQ)

The Motion Sickness History Questionnaire (MSHQ) was developed as a diagnostic tool to assess susceptibility to MS syndrome (From Reason, 1968, as cited in Reason & Brand, 1975). As opposed to other tools that rely on exposure to provocative

conditions, the MSHQ assesses sickness over a wide range of conditions and is based on participants' recall of salient sickening experiences. The MSHQ assesses how frequently the participant is involved in a variety of travel conditions (i.e., cars, buses, trains, small boats, ships, airplanes), how frequently they feel sick in terms of queasiness or nausea, and how frequently sickness results in vomiting while traveling. The MSHQ yields a single sickness score, the higher the score the more susceptible the individual.

Simulator Sickness Questionnaire (SSQ)

The Simulator Sickness Questionnaire (SSQ) was developed by Kennedy et al. (1993). The SSQ was developed to be an accurate measure of MS symptoms in VE. These MS-like symptoms experienced in VE are known as SS. Prior to development of the SSQ, SS was typically assessed using the Pensacola Motion Sickness Questionnaire (MSQ). The MSQ was inappropriate for measuring SS because it contained symptoms that are observed in MS, but not found in SS. The SSQ was developed using existing MSQ data analyzed through a series of factor analyses. The data consisted of over 1,100 MSQs from 10 Navy simulators.

Development of the SSQ consisted of 1,119 pre- and post-exposure pairs of MSQs. The version of the MSQ used contained 28 symptoms. Symptoms selected too infrequently and symptoms with no change in frequency or severity were eliminated as well as symptoms that might give misleading indications. After this was complete, 12 of the original 28 symptoms had been eliminated. Items retained and eliminated can be seen in Figure 3.9.

Symptoms in MSQ and SSQ		
<i>MSQ Symptom</i>	<i>Retained for SSQ</i>	<i>Eliminated for SSQ</i>
General discomfort	X	
Fatigue	X	
Boredom		X
Drowsiness		X
Headache	X	
Eyestrain	X	
Difficulty focusing	X	
Increased salivation	X	
Decreased salivation		X
Sweating	X	
Nausea	X	
Difficulty concentrating	X	
Depression		X
Fullness of head	X	
Blurred vision	X	
Dizziness (eyes open)	X	
Dizziness (eyes closed)	X	
Vertigo	X	
Visual flashbacks		X
Faintness		X
Awareness of breathing		X
Stomach awareness	X	
Decreased appetite		X
Increased appetite		X
Desire to move bowels		X
Confusion		X
Burping	X	
Vomiting		X

Figure 3.9. Items retained and eliminated from MSQ to create SSQ (From Kennedy et al., 1993).

A principle factors analysis was used to determine possible factors that the remaining 16 symptoms fall under. As a result, 3 symptom clusters were identified. Kennedy et al. (1993) identified the clusters as Oculomotor (O; eyestrain, difficulty focusing, blurred vision, headache), Disorientation (D; dizziness, vertigo), and Nausea (N; nausea, stomach awareness, increased salivation, burping). Kennedy et al. (1993) states “the three-factor solution suggested the existence of three (partially) independent symptom clusters, each reflecting the impact of simulator exposure on a different ‘target system’ within the human (p. 208).”

Prior to administration, the researcher should gather information about the participants’ current state of health because the SSQ assumes that the participant is in a usual state of health. During administration, participants respond to the 16 symptoms by indicating how severe they are experienced. Participants answer on a scale of “none, slight, moderate, or severe” with respective raw scores of “0,” “1,” “2,” or “3.” The SSQ yield a Total Severity (TS) score and three subscale scores for oculomotor, disorientation, and nausea subscales. Subscale scores are determined by multiplying the summation of raw scores within a subscale by a constant specific to the subscale. The TS score is determined by multiplying the summation of raw scores from each subscale by a constant specific to the TS score. The highest possible TS score is 235.62.

The SSQ was developed for use with VE systems in general, which includes HMDs, and is the most frequently used to for assessing SS in VEs. The profile that occurs as a result of VE exposure can differ from profiles that occur as the result of other disoriented environments. As indicated in Stanney and Kennedy (1997) indicates that

VE profile as D>N>O, space sickness as O>D>N, SS as O>N>D, and sea and airsickness as N>D>O. Similarly to differing profiles, different systems yield different average SSQ scores. Averages scores of around 10 have been observed on simulator systems, averages of above 20 have been observed in VE systems, and some other systems average as high as 50 (Stannaey & Kennedy, 1997). According to Stanney, Kennedy, and Drexler (1997), from extensive SSQ scores obtained using flight simulators, SSQ scores of 5-10 indicate minimal symptoms, 10-15 indicate significant symptoms, and scores above 20 indicate a bad VE simulator.

Motion Sickness Assessment Questionnaire (MSAQ)

The Motion Sickness Assessment Questionnaire (MSAQ) was developed by Gianaros et al. (2001). It was created as a multidimensional approach to study MS syndrome in terms of its component parts. At the time, the most widely used questionnaires for studying the MS syndrome were the Pensacola Diagnostic Index (PDI) and the MSQ (Gianaros et al., 2001). These MS syndrome assessment tools yielded single MS scores based on composite magnitude of the symptoms, treating MS as a construct varying on a single continuum. The problem with a single score quantification of the MS syndrome is that it lacked the ability to differentiate between individual susceptibility and evocative context.

In the first phase of MSAQ development a list of 87 adjectives generated by 67 participants. Similar adjectives were combined yielding a list of 71 items. The top 34 items were included in the original questionnaire. In the second phase the list of 34

descriptors was distributed to 747 participants for ratings. Items were rated using a 4-point Likert-type scale (0 = not at all, 1 = slightly, 2 = moderately, and 3 = very). Participant rating of descriptors were based on using them to complete the sentence: “When I am motion sick, I feel_____.” Items were then eliminated if at least 50% did not rate them as at least slightly or if the items were ambiguous, yielding 20 items. A principal axis factor analysis was performed and four, five, and six factor solutions were observed. The four factor solution was the most easily interpretable with factors labeled gastrointestinal, central, peripheral, and sopite-related. After performing a confirmatory factor analysis in the third phase, items indicating similar phenomena as compared to other items were eliminated leaving 16 total items. The final version of the MSAQ uses a 10-point scale (0 = not at all and 10 = severely). Overall MSAQ scores were a summation of individual items ratings across all 16 items with a maximum possible score of 160.

Room Layout

Participants were required to locate eight objects in the laboratory during the experimental trials. The objects were the office door, clock, flag, a photocopy of the fire extinguisher, the front door, first aid kit, fan, and the curtain. Locations of these objects can be seen in Figure 3.10. The curtain, front door, and office door are marked with an “X” to indicate that they are objects to be located. Photographs of the actual objects can be viewed in Figure 3.11.

Figure 3.10. Room layout with distance measurements from the participant. A = Participant, B = Office door, C = Clock, D = Flag, E = Photocopy of fire extinguisher, F = Front door, G = First aid, H = Fan, I = Curtain (From Moss, 2008).

Figure 3.11. Photographs of the objected viewed by participants while wearing the HMD.

Procedure

Upon entry to the lab, participants completed the Clemson University Institutional Review Board approved consent form. Participants were screened for problems relating to the stomach, heart, brain, vision, or the inner ear. Participants' visual acuity was screened using a LogMAR chart. Participants wearing contacts were allowed to participate in the study. Participants wearing glasses were not allowed to participant because glasses interfere with HMD use. Participants were also screened for pregnancy, vertigo, and past experience in virtual environments and HMDs. Participants were

excluded from the study if they answered “yes” to any of the screening items. Their motion sickness history was also taken using the MSHQ. Individuals who reported the experience of MS symptoms frequently or easily were excluded from the study.

The participant was then led to the back of the lab for visual measurements. The researcher explained the procedure for collecting dark vergence and dark focus measurements. Then the participant placed their chin in the chinrest and forehead against the headrest of the auto refractometer. The participant was told to look straight ahead and to keep their eyes open. The researcher aligned the auto refractometer to the pupil and iris of the right eye participant and took three measurements and the process was repeated with the left eye of the participant.

The participant was told to move over to the Vergamatic II for the dark vergence measurements. The IPD measure from the auto refractometer was entered into the vergamatic program to set it to the correct IPD for the participant. The participant placed their chin in the chinrest and forehead against the headrest in front of the Vergamatic. The participant was told to look straight ahead and view the faint flashing lights. The participant was instructed, when the dark vergence procedure was explained, that they should use a response box to identify where the flashing lights flash. As the lights flash, the participant should click the “right” button on the response box for lights that flash to the right of center or the “left” button on the response box for lights that flash to the left of center. Practice measurements of dark vergence were taken to assure that the participant was approaching a resting eye state. After several practice measurements, the three pre-experimental measures of dark vergence were taken. The overall dark vergence

posture measurement was the mean of all three pre-experimental measurements of dark vergence.

After the resting oculomotor measurements were taken, the lights were turned on. The participant was taken back to the area where the experimental task was to be performed. The researcher explained the procedure associated with performing the HMD object location task. The researcher identified the objects and locations to be located during the experimental trials. Participants were shown where to stand and provided a 39 $\frac{3}{4}$ " step ladder to use as a hand rail to support balance during the trials. The participant was then put on the HMD and the researcher adjusted the displays to match the IPD of the participant. The lens cap of the high speed camera atop the HMD was removed. The participant then viewed an eye chart to assess any camera adjustments that needed to be made to improve image quality. The lens cap is then replaced. The researcher then administered a pre-practice MSAQ and SSQ.

The HMD task consisted of head movements by the participant while wearing the HMD. The head movements were made to locate objects in the laboratory based on the name and location of the object. A voice recording called out the object name and direction to participants in three second intervals. Object order was randomized. The maximum horizontal head movement was 180°. Participants were instructed to move primarily from the head and neck. Participants were also allowed to make slight shoulder movements if they lack the ability to make the necessary head movement with only head and neck movements. Participants were instructed not to make torso, hips, and leg movements while searching for objects. The researcher informed the participant to center

the object in the center of the displays while performing the task. Between trials, participants were instructed to maintain their position and to look forward at the front door.

Participants performed two 48 second HMD task practice trials before the experimental trials. The practice trials were necessary so the participant could learn the objects and locations as well as the speed of the task. After completion of the practice trials, the researcher administered the MSAQ and SSQ.

After the practice trials, the participants performed 5, 2 minute experimental trials of the HMD task. Between each trial there was a 1 minute break. Each trial was 2 minutes long and consisted of 40 head movements every 3 seconds. The researcher recorded the accuracy of the head movements by viewing the images projected in the displays of the HMD on the computer monitor. During the 1 minute break between each trial, an SSQ was administered. Immediately following the final trial, the MSAQ and SSQ were administered while the participant is still wearing the HMD.

Once the MSAQ and SSQ were completed, the participant was instructed to close their eyes and keep them closed until the researcher told them they could open them again. The HMD was then removed and the participant was given a blind fold/sleep mask to wear. The participant was then instructed to put their hand on the forearm or shoulder of the researcher. The researcher led the participant back to the area where resting oculomotor measurements were taken. Once the participant was in position, the lights were turned off and the blind fold/sleep mask was removed. Dark focus was then measured in the same way as pre-experimental measurements of dark focus. Dark

vergence measurements were then taken, but in contrast to the pre-experimental measurements there were no practice measurements. The lights were then turned on. The participant and researcher then returned to the area where the HMD task was performed. The researcher administered the SSQ and then another SSQ 5 minutes later.

Data Analysis

Data Reduction

The peak (i.e. highest) participant SSQ scores were used to examine SS and the post experimental MSAQ score was used as a measure of MS. Nine SSQ scores (i.e., pre practice, post practice, one after each of the five experimental trials, and two post experiment) were obtained from each participant similarly to Moss and Muth (2011) and Moss, Scisco, and Muth (2008) as well as three MSAQ scores (i.e., one pre practice, one post practice, and one after the final experimental trial). The rationale for the use of peak SSQ scores is twofold. First, peak scores were used in the case that a participant withdrew from the study before completion of all experimental trials. This prevents missing SSQ data during the statistical analyses. Second, MS and SS symptomology onset and severity varies among individuals.

Multiple oculomotor measurements were made with regard to dark vergence and dark focus. Two vergence measurements were provided using the Vergamatic II. The first was in degrees, which was simply the angle of convergence. The second was the meter-angle (MA). The distance associated with MA was measured in meters (m). The distance associated with the MA was derived with the following equation:

$$\text{Distance in meters} = \frac{1}{MA} \quad (7)$$

In the case of dark focus, the Grand Seiko Co., LTD WV-500 Auto-Refractometer provided a spherical and a cylindrical measurement for each eye. The spherical measurement refers to the refractive error of the eye while the cylindrical measurement refers to the astigmatic refractive error of the eye. These two measures were used to derive the spherical equivalent refraction (SER), which provided the accommodative measurement in diopters (D). The SER can be found using the following equation:

$$\text{SER} = \text{sphere} + \frac{1}{2}\text{cylinder} \quad (8)$$

Statistical Tests of Hypotheses

The effects of added latency, frequency, and amplitude on peak SSQ scores were assessed using a series of planned comparisons. An independent samples t-test was performed to assess if there were statistically significant differences in peak SSQ scores between conditions with a frequency of 0 Hz (i.e., conditions 1 & 2) and 0.2 Hz (i.e., conditions 3 & 4). An independent samples t-test was performed to assess if there was a statistically significant differences in peak SSQ scores between constant amplitude (i.e., condition 3) and variable amplitude (i.e., condition 4). An independent samples t-test was performed to assess if there were statistically significant differences in peak SSQ scores between the base system latency (i.e., condition 1) and in the presence of added latency (i.e., condition 2). Paired sample t-tests were performed to assess the statistical significance of the pre to post change in oculomotor resting states. A Pearson's product moment correlation was conducted to determine the relationship between change in dark

vergence (i.e., degrees and MA) from pre to post and peak SSQ scores. Pearson's product moment correlations were conducted to determine the relationship between the change in dark focus in the right and left eye from pre to post and peak SSQ scores.

Exploratory Analyses

The following analyses were performed to determine relationships, but no direct hypotheses were made regarding these relationships in this study. Separate Pearson's product moment correlations were conducted to determine the relationship between pre and post experimental measurements of dark vergence (i.e., degrees and MA) and individual SSQ items and symptom clusters. Pearson's product moment correlations were conducted to determine the relationship between the pre and post experimental measurement of dark focus and individual SSQ items and symptom clusters.

A 2X4 chi-square analysis was performed between participants who withdrew from the study and those participants who completed all experimental trials between participants in all experimental conditions (i.e., baseline, baseline + 200 ms, wave pool, and ocean). This was examined to determine dependence of condition membership on participant withdrawal.

A 4 (condition) X 5 (trial) repeated measures analysis of variance was performed to determine main effects of trial on SS. In this analysis, condition was the between-subjects factor and trial was the within-subjects factor. Where necessary, pairwise comparisons were made using Holm's sequential Bonferroni approach. Five

experimental trials were performed through the course of the study. An SSQ was administered immediately following each experimental trial.

CHAPTER IV

RESULTS

Distribution of SSQ and MSAQ Scores

Data sets were collected from 120 participants. Out of the 120 participants, 11 participants withdrew from the experiment before completion of the 5 experimental trials. All participants who withdrew exhibited common symptomology associated with the experience of SS such as dizziness, nausea, oculomotor symptoms (i.e., blurred vision, difficulty focusing), or headache. Of these participants, 4 reported severe faint-like symptoms. Each of these 4 participants was helped to a seat by the researcher. Two of the participants opted to lie on the floor until faint-like symptoms subsided. During post-experimental debriefing, all 4 participants reported never experiencing similar symptoms in the past.

Frequency distributions of the entire data set for SSQ Peak scores as well as MSAQ scores revealed that a positive skew was present in both. See Figure 4.1 for a histogram showing Peak SSQ scores. See Figure 4.2 for a histogram showing MSAQ scores. All frequency distributions for each individual condition were compared. See Appendices E and F. Each distribution showed similar characteristics. It was determined that the data could be analyzed without transformation because all conditions displayed a similar shape and t-tests and ANOVAs are robust to moderate skew provided the distributions are of similar shape. Nonetheless, to confirm that the skew did not impact the results, the data was also analyzed using a square root transformation to adjust for the

positive skew. See Appendices G and H for post square root transformation frequency distributions by condition. See Figure 4.3 for a histogram of Peak SSQ scores after square root transformation. See Figure 4.4 for a histogram of MSAQ scores after square root transformation.

Figure 4.1. Frequency distribution of peak SSQ scores for the current study.

Figure 4.2. Frequency distribution of MSAQ scores for the current study.

Figure 4.3. Frequency distribution of SSQ peak scores after square root transformation.

Figure 4.4. Frequency distribution of MSAQ scores after square root transformation.

Planned Comparisons

Simulator Sickness Results without Square Root Transform

Samples sizes, means, and standard deviations by condition are presented in Table 4.1. An independent samples t-test was performed between baseline condition and the baseline + 200 ms condition. The baseline condition was not significantly different from the baseline + 200 ms condition, $t(58) = -0.49$, $p = 0.31$, indicating no difference between SSQ peak scores in the baseline condition ($M = 24.81$, $SD = 25.39$) and SSQ peak scores in the baseline + 200 ms condition ($M = 28.55$, $SD = 33.65$; see Figure 4.5). An

independent samples t-test was performed between the wave pool condition and the ocean condition. The wave pool condition was significantly different from the ocean condition, $t(58) = -2.86$, $p = 0.003$, indicating that SSQ peak scores were lower in the wave pool condition ($M = 35.28$, $SD = 34.97$) than SSQ peak scores in the ocean condition ($M = 65.33$, $SD = 45.67$; see Figure 4.6). An independent samples t-test was performed between 0 Hz frequency condition and the 0.2 Hz frequency condition. The 0 Hz frequency condition (i.e., combination of baseline and baseline + 200 ms conditions) was significantly different from the 0.2 Hz frequency condition (i.e., combination of wave pool and ocean conditions), $t(104.59) = -3.50$, $p < 0.001$, indicating that SSQ peak scores were lower in the 0 Hz frequency condition ($M = 26.68$, $SD = 29.61$) than SSQ peak scores in the 0.2 Hz frequency condition ($M = 50.30$, $SD = 43.08$; see Figure 4.7).

Table 4.1. Means and standard deviations (SD) of SSQ peak total scores by condition.

	Mean	SD	N
Baseline	24.80	25.39	30
Baseline + 200 ms	28.55	33.65	30
Wave Pool	35.28	34.97	30
Ocean	65.33	45.67	30
0 Hz	26.68	29.61	60
0.2 Hz	50.30	43.08	60
Total	38.49	38.67	120

Figure 4.5. Mean difference between baseline and baseline + 200 ms conditions with standard error bars.

Figure 4.6. Mean difference between wave pool and ocean conditions with standard error bars

Figure 4.7. Mean difference between 0 Hz and 0.2 Hz conditions with standard error bars.

Simulator Sickness Results with Square Root Transform

Samples sizes, means, and standard deviations by condition are presented in Table 4.2. The results with the square root transformation mirror those without it. An independent samples t-test was performed between baseline condition and the baseline + 200 ms condition. The baseline condition was not significantly different from the baseline + 200 ms condition, $t(58) = -0.05$, $p = 0.48$, indicating no difference between SSQ peak scores in the baseline condition ($M = 4.14$, $SD = 2.84$) and SSQ peak scores in the baseline + 200 ms condition ($M = 4.17$, $SD = 3.41$). An independent samples t-test was performed between the wave pool condition and the ocean condition. The wave pool condition was significantly different from the ocean condition, $t(58) = -3.07$, $p = 0.002$, indicating that SSQ peak scores were lower in the wave pool condition ($M = 5.05$, $SD =$

3.20) than SSQ peak scores in the ocean condition ($M = 7.52$, $SD = 3.04$). An independent samples t-test was performed between 0 Hz frequency condition and the 0.2 Hz frequency condition. The 0 Hz frequency condition was significantly different from the 0.2 Hz frequency condition, $t(118) = -3.61$, $p < 0.001$, indicating that SSQ peak scores were lower in the 0 Hz frequency condition ($M = 4.16$, $SD = 3.11$) than SSQ peak scores in the 0.2 Hz frequency condition ($M = 6.28$, $SD = 3.34$).

Table 4.2. Means and standard deviations (SD) of SSQ peak total scores by condition after square root transform.

	Mean	SD	N
Baseline	4.14	2.84	30
Baseline + 200 ms	4.17	3.41	30
Wave Pool	5.05	3.20	30
Ocean	7.52	3.04	30
0 Hz	4.16	3.11	60
0.2 Hz	6.28	3.34	60
Total	5.22	3.38	120

Motion Sickness Results without Square Root Transform

Samples sizes, means, and standard deviations by condition are presented in Table 4.3. An independent samples t-test was performed between baseline condition and the baseline + 200 ms condition. The baseline condition was not significantly different from the baseline + 200 ms condition, $t(58) = -0.53$, $p = 0.30$, indicating no difference between MSAQ scores in the baseline condition ($M = 25.80$, $SD = 12.07$) and MSAQ scores in the

baseline + 200 ms condition ($M = 27.97$, $SD = 18.64$; see Figure 4.8). An independent samples t-test was performed between the wave pool condition and the ocean condition. The wave pool condition was significantly different from the ocean condition, $t(58) = -2.67$, $p = 0.005$, indicating that MSAQ scores were lower in the wave pool condition ($M = 32.30$, $SD = 19.71$) than MSAQ scores in the ocean condition ($M = 48.73$, $SD = 27.37$; see Figure 4.9). An independent samples t-test was performed between 0 Hz frequency condition and the 0.2 Hz frequency condition. The 0 Hz frequency condition was significantly different from the 0.2 Hz frequency condition, $t(98.78) = -3.58$, $p < 0.001$, indicating that MSAQ scores were lower in the 0 Hz frequency condition ($M = 26.88$, $SD = 15.61$) than MSAQ scores in the 0.2 Hz frequency condition ($M = 40.52$, $SD = 25.06$; see Figure 4.10).

Table 4.3. Means and standard deviations (SD) of MSAQ scores by condition.

	Mean	SD	N
Baseline	25.80	12.07	30
Baseline + 200 ms	27.97	18.64	30
Wave Pool	32.30	19.71	30
Ocean	48.73	27.37	30
0 Hz	26.88	15.61	60
0.2 Hz	40.52	25.06	60
Total	33.70	21.88	120

Figure 4.8. Mean difference between baseline and baseline + 200 ms conditions with standard error bars.

Figure 4.9. Mean difference between wave pool and ocean conditions with standard error bars.

Figure 4.10. Mean difference between 0 Hz and 0.2 Hz conditions with standard error bars.

Motion Sickness Results with Square Root Transform

Samples sizes, means, and standard deviations by condition are presented in Table 4.4. The results with the square root transformation mirrored those without the transformation. An independent samples t-test was performed between baseline condition and the baseline + 200 ms condition. The baseline condition was not significantly different from the baseline + 200 ms condition, $t(58) = -0.21, p = 0.42$, indicating no difference between MSAQ scores in the baseline condition ($M = 3.17, SD = 0.39$) and MSAQ scores in the baseline + 200 ms condition ($M = 3.19, SD = 0.49$). An independent samples t-test was performed between the wave pool condition and the ocean condition. The wave pool condition was significantly different from the ocean condition, $t(58) = -2.96, p = 0.002$, indicating that MSAQ scores were lower in the wave

pool condition ($M = 3.33$, $SD = 0.53$) than MSAQ scores in the ocean condition ($M = 3.74$, $SD = 0.55$). An independent samples t-test was performed between 0 Hz frequency condition and the 0.2 Hz frequency condition. The 0 Hz frequency condition was significantly different from the 0.2 Hz frequency condition, $t(110.43) = -3.55$, $p < 0.001$, indicating that MSAQ scores were lower in the 0 Hz frequency condition ($M = 3.18$, $SD = 0.44$) than MSAQ scores in the 0.2 Hz frequency condition ($M = 3.53$, $SD = 0.57$).

Table 4.4. Means and standard deviations (SD) of MSAQ scores by condition after square root transform.

	Mean	SD	N
Baseline	3.17	0.39	30
Baseline + 200 ms	3.19	0.49	30
Wave Pool	3.33	0.53	30
Ocean	3.74	0.55	30
0 Hz	3.18	0.44	60
0.2 Hz	3.53	0.57	60
Total	3.36	0.54	120

Oculomotor Resting States

Attempts were made to collect dark vergence and dark focus data from 120 participants. Due to measurement error, participant error, drop-outs, and technical errors, complete dark vergence posture data sets (i.e., pre and post measurements) were collected from 89/120 participants. Pre experimental measurements of dark vergence were collected from 97/120 participants. Due to measurement error, participant error, drop-

outs, and technical errors, complete dark focus data sets (i.e., pre and post measurements) were collected from 99/120 participants. Pre experimental measurements of dark focus were collected from 111/120 participants. Analysis of the data for oculomotor resting states indicated that no transformation was necessary prior to further analysis. See Appendices I thru O for frequency distributions of oculomotor resting states (dark vergence and dark focus).

Dark Vergence

Samples sizes, means, and standard deviations for dark vergence measurements pre and post as well as the change from pre to post are presented in Table 4.5. A paired samples t-test was performed between dark vergence degrees pre and post measurements. The pre dark vergence degrees were significantly different from post dark vergence degrees, $t(88) = -3.47, p < 0.01$, indicating pre dark vergence degrees measurements were lower ($M = 3.35$ deg, $SD = 1.42$ deg) than post dark vergence degrees measurements ($M = 3.75$ deg, $SD = 1.29$ deg). A paired samples t-test was performed between dark vergence MA pre and post measurements. Pre dark vergence MA was significantly different from post dark vergence MA, $t(88) = -3.34, p < 0.01$, indicating pre dark vergence MA measurements were lower ($M = 0.97$, $SD = 0.40$) than post dark vergence MA measurements ($M = 1.07$, $SD = 0.35$). A paired samples t-test was performed between dark vergence distance in meters pre and post measurements. Pre dark vergence distance was significantly different from post dark vergence distance, $t(88) = 3.58, p < 0.01$, indicating pre dark vergence distance measurements were higher ($M = 1.29$ m, $SD =$

0.77 m) than post dark vergence distance measurements ($M = 1.04$ m, $SD = 0.37$ m).

Pearson's product moment correlations were performed for changes in dark vergence measurements (i.e., degrees, MA, and distance in meters) and SSQ peak scores. No significant correlations were found between dark vergence measurements and SSQ peak scores, see Table 4.6.

Table 4.5. Means and standard deviations (SD) for dark vergence measurements from pre to post and change from pre to post.

	Mean	SD	N
Pre Dark Vergence Degrees	3.36	1.38	97
Post Dark Vergence Degrees	3.75	1.29	89
Pre Dark Vergence MA	0.97	0.40	97
Post Dark Vergence MA	1.07	0.35	89
Pre Dark Vergence Distance in Meters	1.28	0.75	97
Post Dark Vergence Distance in Meters	1.04	0.39	89
Dark Vergence Degree Change from Pre to Post	-0.40	1.08	89
Dark Vergence MA Change from Pre to Post	-0.11	0.31	89
Dark Vergence Distance Change in Meters from Pre to Post	0.25	0.67	89

Table 4.6. Correlation matrix for change in dark vergence measures from pre to post, peak SSQ scores, and MSAQ scores.

	1	2	3	4
1 Change in Vergence Degree from Pre to Post				
2 Change in Vergence MA from Pre to Post	.994**			
3 Change in Vergence Distance in Meters from Pre to Post	-.660**	-.675**		
4 Peak SSQ Score	.083	.075	-.095	
5 MSAQ Score	.077	.062	-.060	.861**

**Significant correlations at $p < 0.01$

*Significant correlations at $p < 0.05$

Dark Focus

Samples sizes, means, and standard deviations for dark focus measurements pre and post as well as the change from pre to post are presented in Table 4.7. A paired samples t-test was performed between dark focus pre and post measurements for the left eye. The pre dark focus measurement of the left eye was significantly different from post dark focus measurement of the left eye, $t(98) = -3.55, p < 0.01$, indicating pre dark focus measurements were lower ($M = 0.30$ D, $SD = 0.90$ D) than post dark focus measurements ($M = 0.49$ D, $SD = 0.96$ D). A paired samples t-test was performed between dark focus pre and post measurements for the right eye. The pre dark focus measurement of the right eye was not significantly different from post dark focus measurement of the right eye, $t(98) = -1.30, p = 0.20$, indicating no difference between pre dark focus measurements ($M = 0.41$ D, $SD = 0.77$ D) and post dark focus measurements ($M = 0.48$ D, $SD = 0.79$ D). Pearson's product moment correlations were performed for changes dark focus measurements (i.e., left and right eyes) and SSQ peak scores. No significant correlations were found between dark focus measurements and SSQ peak scores, see Table 4.8.

Table 4.7. Means and standard deviations (SD) for dark focus measurements from pre to post and change from pre to post.

	Mean	SD	N
Pre Dark Focus (Left Eye)	0.34	0.91	111
Post Dark Focus (Left Eye)	0.49	0.96	99
Pre Dark Focus (Right Eye)	0.47	0.83	111
Post Dark Focus (Right Eye)	0.48	0.79	99
Dark Focus Change from Pre to Post (Left Eye)	-0.20	0.55	99
Dark Focus Change from Pre to Post (Right Eye)	-0.06	0.48	99

Table 4.8. Correlation matrix for change in dark focus measures from pre to post for the left and right eye, peak SSQ scores, and MSAQ scores

	1	2	3
1 Change in Dark Focus Left Eye			
2 Change in Dark Focus Right Eye	.431**		
3 Peak SSQ Score	.113	.014	
4 MSAQ Score	.102	-.011	.861**

**Significant correlations at $p < 0.01$

*Significant correlations at $p < 0.05$

Exploratory Analyses

Frequency of Latency and Simulator Sickness

A one-way ANOVA was performed to further explore the effect of the latency manipulation (i.e., added latency, frequency of latency, and amplitude of latency) on peak SSQ scores. The one-way ANOVA found a significant main effect, $F(3, 116) = 8.00, p < 0.01$, for the latency manipulation. Fisher's LSD was used to make pairwise comparisons between the four conditions. The results indicated that the only condition that significantly differed from any other was the ocean condition, which significantly differed from every other condition on peak SSQ scores.

Participant Withdrawal

Due to the high number of participants ($11/120 = 9.2\%$) who withdrew from the experiment, participant withdrawal was examined. Participant withdraw was defined as any time a participant dropped out of the experiment prior to completion of all 5 experimental trials. This analysis included all 120 participants, 30 participants being present in each of the 4 conditions. A total of 11 participants withdrew from the experiment prior to completion of the 5 experimental trials. Seven participants withdrew from the ocean condition, while 2 withdrew from both the baseline + 200 ms condition and from the wave pool condition, while no participants withdrew from the baseline condition.

A 2X4 chi-square test of independence was performed. The test indicated a significant relationship between condition and participant withdrawal, $\chi^2(3, N = 120) =$

10..71, $p = 0.013$. See Table 4.9. The χ^2 expected cell count assumption was violated because all four cells (50.0%) had an expected count at less than five. As a result, Fisher's exact test was performed. It was found that condition membership was related to participant withdraw (3, $N = 120$, $p = 0.013$, two-tailed Fisher's exact test).

Table 4.9. Participant Withdrawal * Condition Crosstabulation

			Condition				Total
			Baseline	Baseline + 200 ms	Wave Pool	Ocean	
Participant Withdrawal	Complete	Count	30	28	28	23	109
		Expected Count	27.3	27.3	27.3	27.3	109.0
	Withdrew	Count	0	2	2	7	11
		Expected Count	2.8	2.8	2.8	2.8	11.0
Total		Count	30	30	30	30	120
		Expected Count	30.0	30.0	30.0	30.0	120.0

Effect of Trial

The effect of trial was examined using participants' SSQ scores that were administered immediately following each experimental trial. SSQ scores obtained from all participants in the experiment were used for the analysis ($N = 120$).

A 4 (condition) X 5 (trial) repeated measures ANOVA was performed across condition to examine the effects of trial. See Table 4.10 for sample sizes by condition within each trial from the repeated measures ANOVA.

Table 4.10. Sample size by condition within each trial.

Trial	Baseline	Baseline + 200 ms	Wave Pool	Ocean
Trial 1	30	29	28	25
Trial 2	30	29	28	25
Trial 3	30	29	28	25
Trial 4	30	29	28	25
Trial 5	30	29	28	25

Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(9) = 186.94$, $p < 0.001$. Degrees of freedom were corrected using the Greenhouse-Geisser estimates of sphericity, $\epsilon = 0.52$. Results indicated a significant effect of trial on SSQ scores, $F(2.08, 224.15) = 61.84$, $p < 0.001$. This indicated that SSQ scores increased across experimental trial. See Figure 4.11 for the effect of trial on mean SSQ total score. See Figure 4.12 for the effect of trial on mean SSQ total score by condition.

Figure 4.11. Effect of trial on mean SSQ total score with standard error bars.

Figure 4.12. Effect of trial on SSQ total score by condition.

Post hoc pairwise comparisons using Holm's sequential Bonferroni approach indicated significant differences between all experimental trials. Mean SSQ total scores were significantly higher in trial 5 as compared to all other trials. Mean SSQ total scores were significantly higher in trial 4 as compared to trials 1, 2, and 3. Mean SSQ total scores were significantly higher in trial 3 as compared to trials 1 and 2. Mean SSQ total scores were significantly higher in trial 2 as compared to trial 1. In summary, mean SSQ total scores increased as trials increased.

Oculomotor Resting States and Simulator Sickness

Pearson's product moment correlations were performed to determine if there was a relationship between oculomotor resting states (i.e., dark vergence and dark focus measurements) and SSQ clusters and symptom peak scores.

Usable pre dark vergence measurement (i.e., degrees, MA, and distance in meters) data sets were gathered from 97/120 participants. Usable post dark vergence measurements and change in dark vergence measurements data sets were gathered from 89/120 participants. No significant correlations were found between any dark vergence measurements and SSQ peak cluster scores, see Table 4.11. No significant correlations were found between pre dark vergence measurements and SSQ symptom peak scores. Peak stomach awareness scores were positively correlated with post dark vergence degrees, $r(87) = 0.22, p < 0.05$, and post dark vergence MA, $r(87) = 0.26, p < 0.05$. Peak headache scores were positively correlated with the change in dark vergence degrees, $r(87) = 0.33, p < 0.05$, and the change in dark vergence MA, $r(87) = 0.33, p < 0.05$. See

Tables 4.12-4.15 for correlation matrices for dark vergence measures and SSQ item scores.

Table 4.11. Correlation matrix for dark vergence measures and peak SSQ cluster (i.e., nausea, oculomotor, and disorientation) scores.

	1	2	3	4	5	6	7	8	9	10	11
1 Pre Vergence Degree											
2 Post Vergence Degree	.687**										
3 Pre Vergence Meter Angle	.982**	.642**									
4 Post Vergence Meter Angle	.683**	.974**	.677**								
5 Pre Vergence Distance in Meters	-.807**	-.505**	-.816**	-.526**							
6 Post Vergence Distance in Meters	-.611**	-.861**	-.610**	-.896**	.509**						
7 Change in Vergence Degree from Pre to Post	.492**	-.295**	.522**	-.269*	-.454**	.228*					
8 Change in Vergence MA from Pre to Post	.502**	-.278**	.533**	-.261*	-.466**	.229*	.994**				
9 Change in Vergence Distance in Meters from Pre to Post	-.579**	-0.084	-.591**	-0.088	.864**	0.007	-.660**	-.675**			
10 Peak Nausea	0.038	0.069	0.037	0.076	-0.046	-0.033	0.033	0.025	-0.035		
11 Peak Oculomotor	0.068	-0.01	0.061	-0.009	-0.092	0.021	0.138	0.127	-0.134	.839**	
12 Peak Disorientation	0.018	0.03	0.015	0.033	-0.064	0	0.048	0.044	-0.095	.888**	.863**

**Significant correlations at $p < 0.01$

*Significant correlations at $p < 0.05$

Table 4.12. Correlation matrix for dark vergence degree measures and peak SSQ item scores.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Pre Vergence Degree																	
2 Post Vergence Degree	.687**																
3 General Discomfort	0.106	0.07															
4 Fatigue	0.087	0.007	.665**														
5 Headache	0.114	-0.17	.496**	.488**													
6 Eyestrain	0.027	-0.069	.458**	.482**	.445**												
7 Difficulty Focusing	0.063	0.091	.580**	.523**	.483**	.625**											
8 Increased Salivation	0.118	0.026	.330**	.430**	.370**	.496**	.311**										
9 Sweating	-0.072	-0.003	.567**	.483**	.350**	.341**	.415**	.239**									
10 Nausea	0.01	0.027	.624**	.523**	.325**	.298**	.342**	.380**	.502**								
11 Difficulty Concentrating	0.033	0.065	.641**	.573**	.380**	.561**	.765**	.326**	.496**	.394**							
12 Fullness of Head	-0.01	-0.013	.547**	.575**	.468**	.472**	.414**	.436**	.473**	.550**	.540**						
13 Blurred Vision	-0.054	0.023	.534**	.519**	.325**	.495**	.513**	.421**	.300**	.423**	.533**	.578**					
14 Dizzy Eyes Open	-0.063	-0.04	.509**	.614**	.303**	.406**	.323**	.255**	.501**	.563**	.463**	.472**	.461**				
15 Dizzy Eyes Closed	0.038	0.009	.501**	.492**	.402**	.468**	.416**	.302**	.421**	.526**	.483**	.534**	.460**	.616**			
16 Vertigo	0.115	0.152	.301**	.245**	.205*	.330**	.258**	.439**	.260**	.233*	.243**	.267**	.388**	.312**	.266**		
17 Stomach Awareness	0.143	.220*	.562**	.580**	.338**	.383**	.331**	.528**	.528**	.703**	.465**	.667**	.463**	.554**	.608**	.334**	
18 Burping	0.174	0.087	0.131	.226*	0.154	.250**	0.085	.421**	0.131	.243**	0.099	.245**	0.166	0.07	.358**	0.084	.428**

**Significant correlations at $p < 0.01$ *Significant correlations at $p < 0.05$

Table 4.13. Correlation matrix for dark vergence MA measures and peak SSQ item scores.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Pre Vergence Meter Angle																	
2 Post Vergence Meter Angle	.677**																
3 General Discomfort	0.105	0.07															
4 Fatigue	0.059	-0.013	.665**														
5 Headache	0.138	-0.152	.496**	.488**													
6 Eyestrain	0.006	-0.074	.458**	.482**	.445**												
7 Difficulty Focusing	0.045	0.083	.580**	.523**	.483**	.625**											
8 Increased Salivation	0.094	0.023	.330**	.430**	.370**	.496**	.311**										
9 Sweating	-0.079	-0.008	.567**	.483**	.350**	.341**	.415**	.239**									
10 Nausea	0.019	0.039	.624**	.523**	.325**	.298**	.342**	.380**	.502**								
11 Difficulty Concentrating	0.02	0.062	.641**	.573**	.380**	.561**	.765**	.326**	.496**	.394**							
12 Fullness of Head	0.003	0.004	.547**	.575**	.468**	.472**	.414**	.436**	.473**	.550**	.540**						
13 Blurred Vision	-0.057	0.036	.534**	.519**	.325**	.495**	.513**	.421**	.300**	.423**	.533**	.578**					
14 Dizzy Eyes Open	-0.057	-0.027	.509**	.614**	.303**	.406**	.323**	.255**	.501**	.563**	.463**	.472**	.461**				
15 Dizzy Eyes Closed	0.017	-0.025	.501**	.492**	.402**	.468**	.416**	.302**	.421**	.526**	.483**	.534**	.460**	.616**			
16 Vertigo	0.105	0.161	.301**	.245**	.205**	.330**	.258**	.439**	.260**	.233**	.243**	.267**	.388**	.312**	.266**		
17 Stomach Awareness	0.16	.256*	.562**	.580**	.338**	.383**	.331**	.528**	.528**	.703**	.465**	.667**	.463**	.554**	.608**	.334**	
18 Burping	0.174	0.105	0.131	.226*	0.154	.250**	0.085	.421**	0.131	.243**	0.099	.245**	0.166	0.07	.358**	0.084	.428**

**Significant correlations at $p < 0.01$ *Significant correlations at $p < 0.05$

Table 4.14. Correlation matrix for dark vergence distance measures and peak SSQ item scores.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Pre Vergence Distance																	
2 Post Vergence Distance	.509**																
3 General Discomfort	-0.09	-0.033															
4 Fatigue	-0.053	-0.002	.665**														
5 Headache	-0.134	0.105	.496**	.488**													
6 Eyestrain	-0.063	0.068	.458**	.482**	.445**												
7 Difficulty Focusing	-0.083	-0.056	.580**	.523**	.483**	.625**											
8 Increased Salivation	-0.106	0.073	.330**	.430**	.370**	.496**	.311**										
9 Sweating	0.035	-0.049	.567**	.483**	.350**	.341**	.415**	.239**									
10 Nausea	-0.055	0.031	.624**	.523**	.325**	.298**	.342**	.380**	.502**								
11 Difficulty Concentrating	-0.079	-0.047	.641**	.573**	.380**	.561**	.765**	.326**	.496**	.394**							
12 Fullness of Head	0.002	0.025	.547**	.575**	.468**	.472**	.414**	.436**	.473**	.550**	.540**						
13 Blurred Vision	-0.004	0.009	.534**	.519**	.325**	.495**	.513**	.421**	.300**	.423**	.533**	.578**					
14 Dizzy Eyes Open	-0.082	0.003	.509**	.614**	.303**	.406**	.323**	.255**	.501**	.563**	.463**	.472**	.461**				
15 Dizzy Eyes Closed	-0.016	0.022	.501**	.492**	.402**	.468**	.416**	.302**	.421**	.526**	.483**	.534**	.460**	.616**			
16 Vertigo	-0.096	-0.153	.301**	.245**	.205*	.330**	.258**	.439**	.260**	.233*	.243**	.267**	.388**	.312**	.266**		
17 Stomach Awareness	-0.068	-0.183	.562**	.580**	.338**	.383**	.331**	.528**	.528**	.703**	.465**	.667**	.463**	.554**	.608**	.334**	
18 Burping	-0.022	-0.061	0.131	.226*	0.154	.250**	0.085	.421**	0.131	.243**	0.099	.245**	0.166	0.07	.358**	0.084	.428**

**Significant correlations at $p < 0.01$ *Significant correlations at $p < 0.05$

Table 4.15. Correlation matrix for change dark vergence measures and peak SSQ item scores.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 Change in Vergence Degree																		
2 Change in Vergence MA	.994**																	
3 Change in Vergence Distance	-.660**	-.675**																
4 General Discomfort	0.079	0.081	-0.07															
5 Fatigue	0.124	0.108	-0.05	.665**														
6 Headache	.326**	.326**	-0.21	.496**	.488**													
7 Eyestrain	0.17	0.149	-0.15	.458**	.482**	.445**												
8 Difficulty Focusing	0.013	0.004	-0.09	.580**	.523**	.483**	.625**											
9 Increased Salivation	0.191	0.17	-0.2	.330**	.430**	.370**	.496**	.311**										
10 Sweating	-0.086	-0.095	0.101	.567**	.483**	.350**	.341**	.415**	.239**									
11 Nausea	0.032	0.03	-0.08	.624**	.523**	.325**	.298**	.342**	.380**	.502**								
12 Difficulty Concentrating	0.021	0.01	-0.09	.641**	.573**	.380**	.561**	.765**	.326**	.496**	.394**							
13 Fullness of Head	0.024	0.02	-0.01	.547**	.575**	.468**	.472**	.414**	.436**	.473**	.550**	.540**						
14 Blurred Vision	-0.079	-0.09	-0.03	.534**	.519**	.325**	.495**	.513**	.421**	.300**	.423**	.533**	.578**					
15 Dizzy Eyes Open	0.021	0.02	-0.12	.509**	.614**	.303**	.406**	.323**	.255**	.501**	.563**	.463**	.472**	.461**				
16 Dizzy Eyes Closed	0.074	0.084	-0.03	.501**	.492**	.402**	.468**	.416**	.302**	.421**	.526**	.483**	.534**	.460**	.616**			
17 Vertigo	0.061	0.054	-0.08	.301**	.245**	.205**	.330**	.258**	.439**	.260**	.233**	.243**	.267**	.388**	.312**	.266**		
18 Stomach Awareness	0.034	0.034	0.015	.562**	.580**	.338**	.383**	.331**	.528**	.528**	.703**	.465**	.667**	.463**	.554**	.608**	.334**	
19 Burping	0.163	0.146	0.008	0.131	.226*	0.154	.250**	0.085	.421**	0.131	.243**	0.099	.245**	0.166	0.07	.358**	0.084	.428**

**Significant correlations at p<0.01

*Significant correlations at p<0.05

Usable pre dark focus measurements data sets for each eye were gathered from 111/120 participants. Usable post dark focus measurements and change in dark focus measurements data sets for each eye were gathered from 99/120 participants. No significant correlations were found between any dark focus measurements and SSQ peak cluster scores, see Table 4.16. Peak fatigue scores were positively correlated with pre dark focus measurements for the left eye, $r(109) = 0.21, p < 0.05$, and pre dark focus measurements for the right eye, $r(109) = 0.24, p < 0.05$. Peak blurred vision scores were positively correlated with pre dark focus measurements for the right eye, $r(109) = 0.19, p < 0.05$. Peak burping scores were positively correlated with pre dark focus measurements of the left eye, $r(109) = 0.21, p < 0.05$. No significant correlations were found between post dark focus measurements and SSQ symptom peak scores. No significant correlations were found between the change in dark focus measurements and SSQ symptom peak scores. See Tables 4.17-4.19 for correlation matrices for dark focus and SSQ item scores.

Table 4.16. Correlation matrix for dark focus measures for left and right eyes and peak SSQ cluster (i.e., nausea, oculomotor, and disorientation) scores.

	1	2	3	4	5	6	7	8
1 Pre Dark Focus Left Eye								
2 Post Dark Focus Left Eye	.828**							
3 Pre Dark Focus Right Eye	.836**	.727**						
4 Post Dark Focus Right Eye	.790**	.851**	.810**					
5 Change in Dark Focus Left Eye	0.19	-.394**	0.068	-0.196				
6 Change in Dark Focus Right Eye	0.009	-.238*	.266**	-.350**	.431**			
7 Peak Nausea	0.074	-0.011	0.104	0.074	0.081	-0.035		
8 Peak Oculomotor	0.093	-0.029	0.185	0.059	0.101	0.063	.839**	
9 Peak Disorientation	0.133	0.013	0.167	0.121	0.144	-0.004	.888**	.863**

**Significant correlations at $p < 0.01$

*Significant correlations at $p < 0.05$

Table 4.17. Correlation matrix for dark focus measures for left eye and peak SSQ item scores.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Pre Dark Focus Left Eye																	
2 Post Dark Focus Left Eye	.828**																
3 General Discomfort	-0.004	-0.08															
4 Fatigue	.209*	0.115	.665**														
5 Headache	0.039	-0.062	.496**	.488**													
6 Eyestrain	-0.025	-0.089	.458**	.482**	.445**												
7 Difficulty Focusing	0.034	-0.017	.580**	.523**	.483**	.625**											
8 Increased Salivation	0.071	0.03	.330**	.430**	.370**	.496**	.311**										
9 Sweating	0.036	0.088	.567**	.483**	.350**	.341**	.415**	.239**									
10 Nausea	0.156	0.048	.624**	.523**	.325**	.298**	.342**	.380**	.502**								
11 Difficulty Concentrating	0.006	-0.083	.641**	.573**	.380**	.561**	.765**	.326**	.496**	.394**							
12 Fullness of Head	0.148	-0.011	.547**	.575**	.468**	.472**	.414**	.436**	.473**	.550**	.540**						
13 Blurred Vision	0.159	0.074	.534**	.519**	.325**	.495**	.513**	.421**	.300**	.423**	.533**	.578**					
14 Dizzy Eyes Open	0.037	-0.061	.509**	.614**	.303**	.406**	.323**	.255**	.501**	.563**	.463**	.472**	.461**				
15 Dizzy Eyes Closed	0.001	-0.028	.501**	.492**	.402**	.468**	.416**	.302**	.421**	.526**	.483**	.534**	.460**	.616**			
16 Vertigo	-0.041	-0.047	.301**	.245**	.205*	.330**	.258**	.439**	.260**	.233*	.243**	.267**	.388**	.312**	.266**		
17 Stomach Awareness	0.076	-0.003	.562**	.580**	.338**	.383**	.331**	.528**	.528**	.703**	.465**	.667**	.463**	.554**	.608**	.334**	
18 Burping	.208*	0.144	0.131	.226*	0.154	.250**	0.085	.421**	0.131	.243**	0.099	.245**	0.166	0.07	.358**	0.084	.428**

**Significant correlations at $p < 0.01$ *Significant correlations at $p < 0.05$

Table 4.18. Correlation matrix for dark focus measures for right eye and peak SSQ item scores.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Pre Dark Focus Right Eye																	
2 Post Dark Focus Right Eye	.810**																
3 General Discomfort	0.029	-0.103															
4 Fatigue	.241*	0.143	.665**														
5 Headache	0.102	0.013	.496**	.488**													
6 Eyestrain	0.087	0.007	.458**	.482**	.445**												
7 Difficulty Focusing	0.106	0.048	.580**	.523**	.483**	.625**											
8 Increased Salivation	0.073	0.117	.330**	.430**	.370**	.496**	.311**										
9 Sweating	0.018	0.106	.567**	.483**	.350**	.341**	.415**	.239**									
10 Nausea	0.175	0.137	.624**	.523**	.325**	.298**	.342**	.380**	.502**								
11 Difficulty Concentrating	0.097	0.028	.641**	.573**	.380**	.561**	.765**	.326**	.496**	.394**							
12 Fullness of Head	0.166	0.049	.547**	.575**	.468**	.472**	.414**	.436**	.473**	.550**	.540**						
13 Blurred Vision	.190*	0.142	.534**	.519**	.325**	.495**	.513**	.421**	.300**	.423**	.533**	.578**					
14 Dizzy Eyes Open	0.065	0.007	.509**	.614**	.303**	.406**	.323**	.255**	.501**	.563**	.463**	.472**	.461**				
15 Dizzy Eyes Closed	-0.003	0.024	.501**	.492**	.402**	.468**	.416**	.302**	.421**	.526**	.483**	.534**	.460**	.616**			
16 Vertigo	-0.076	0.001	.301**	.245**	.205*	.330**	.258**	.439**	.260**	.233*	.243**	.267**	.388**	.312**	.266**		
17 Stomach Awareness	0.095	0.065	.562**	.580**	.338**	.383**	.331**	.528**	.528**	.703**	.465**	.667**	.463**	.554**	.608**	.334**	
18 Burping	0.146	0.193	0.131	.226*	0.154	.250**	0.085	.421**	0.131	.243**	0.099	.245**	0.166	0.07	.358**	0.084	.428**

**Significant correlations at $p < 0.01$ *Significant correlations at $p < 0.05$

Table 4.19. Correlation matrix for change in dark focus measures for left and right eye and peak SSQ item scores.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 Change in Dark Focus Left Eye																	
2 Change in Dark Focus Right Eye	.431**																
3 General Discomfort	0.029	0.045															
4 Fatigue	0.043	-0.001	.665**														
5 Headache	0.126	0.113	.496**	.488**													
6 Eyestrain	0.121	0.124	.458**	.482**	.445**												
7 Difficulty Focusing	0.023	0	.580**	.523**	.483**	.625**											
8 Increased Salivation	0.137	0.023	.330**	.430**	.370**	.496**	.311**										
9 Sweating	-0.073	-0.15	.567**	.483**	.350**	.341**	.415**	.239**									
10 Nausea	0.082	-0.072	.624**	.523**	.325**	.298**	.342**	.380**	.502**								
11 Difficulty Concentrating	0.069	0.006	.641**	.573**	.380**	.561**	.765**	.326**	.496**	.394**							
12 Fullness of Head	0.154	0.058	.547**	.575**	.468**	.472**	.414**	.436**	.473**	.550**	.540**						
13 Blurred Vision	0.061	-0.051	.534**	.519**	.325**	.495**	.513**	.421**	.300**	.423**	.533**	.578**					
14 Dizzy Eyes Open	0.086	-0.002	.509**	.614**	.303**	.406**	.323**	.255**	.501**	.563**	.463**	.472**	.461**				
15 Dizzy Eyes Closed	0.108	0.005	.501**	.492**	.402**	.468**	.416**	.302**	.421**	.526**	.483**	.534**	.460**	.616**			
16 Vertigo	0.178	0.032	.301**	.245**	.205**	.330**	.258**	.439**	.260**	.233**	.243**	.267**	.388**	.312**	.266**		
17 Stomach Awareness	0.082	0.007	.562**	.580**	.338**	.383**	.331**	.528**	.528**	.703**	.465**	.667**	.463**	.554**	.608**	.334**	
18 Burping	0.174	0.001	0.131	.226*	0.154	.250**	0.085	.421**	0.131	.243**	0.099	.245**	0.166	0.07	.358**	0.084	.428**

**Significant correlations at $p < 0.01$ *Significant correlations at $p < 0.05$

CHAPTER V

DISCUSSION

The primary purpose of this study was to examine the role of latency in HMD generated SS. The findings support that additional latency alone is not the critical factor. Rather it is variability in latency, specifically varying amplitude of latency that appears to contribute to increased sickness. Changes in the frequency of latency may play a role, but the results of the current study are unclear on this issue.

Discussion of Simulator Sickness and Motion Sickness Results

The analyses of the SSQ peak and MSAQ data with and without a square root transform of the data yielded similar results for the added latency, amplitude of latency, and frequency of latency. The hypothesis that a frequency of latency of 0.2 Hz would yield a higher level of sickness than frequency of latency of 0 Hz was partially supported. When the wave pool and ocean conditions were collapsed, higher SSQ peak and MSAQ scores were observed than when the baseline and the baseline + 200 ms conditions were collapsed. Prior to the current study, no study of SS in an HMD had attempted to determine a causal relationship between frequency of latency and SS. Although the relationship between frequency of latency and SS has not been researched previously, the findings in the current study are in agreement with the considerable body of research suggesting that exposure to low frequency motion between 0.1 Hz and 1.0 Hz yields increased MS compared to other frequencies of motion (Alexander et al., 1947; O'Hanlon

& McCauley, 1974; Lawther & Griffin, 1988; Golding & Markey, 1996; Golding et al., 1997; Golding et al., 2001; Duh et al., 2004). Prior research on frequency of motion has been performed in real world motion settings as opposed to an HMD VE setting.

It should be noted however, that the exploratory ANOVA revealed a significant main effect for the latency manipulations. Pairwise comparisons using Fisher's LSD indicated that the only condition which varied significantly from others was the ocean condition. Therefore, the 0.2 Hz effect observed in the current study could be completely due to an interaction of changing amplitude and frequency of latency rather than changing the frequency alone, as the wave pool condition did not differ significantly from the 0 Hz conditions. The results of the current study indicate that 0.2 Hz frequency may cause higher levels of sickness than the 0 Hz frequency, but this cannot be fully confirmed because of the possibility of the amplitude by frequency interaction. Future studies, discussed below, would examine the amplitude by frequency interaction. As this was the first study to examine the effect of varying latency it simply was not possible to anticipate this interaction and have enough conditions to examine every possible latency effect.

The hypothesis that varying amplitude of latency would yield a higher level of sickness compared to fixed amplitude of latency was supported. It was found that the ocean condition, which had varying amplitude of latency, yielded higher SSQ peak and MSAQ scores than the wave pool condition which had fixed amplitude of latency. No prior research existed regarding the relationship between amplitude of latency of the experience of SS. However, past studies indirectly support the importance of varying

amplitude of latency. Wu et al. (2011) reported that head tracking sensors produce varying amplitude of latency due to tracking sensor error. Previous studies such as DiZio and Lackner (1997), that found increasing latency resulted in increasing sickness, had a head tracker incorporated into their experimental situation. In studies where a head tracker was employed, the sensor error would not have been controlled by the researcher, thereby adding variability to the latency manifesting itself as varying amplitude of latency. This inadvertent manipulation of amplitude of latency would explain why DiZio and Lackner (1997) found an effect for latency on SS while Moss and Muth (2011) did not. Hence, the current findings point to varying amplitude of latency as an important variable in the genesis of HMD induced SS.

The hypothesis that added latency would yield higher SS levels compared to no added latency was not supported. A conflict in the literature exists regarding whether or not latency has an effect on SS. Multiple research studies (Wildzunas et al., 1996; DiZio & Lackner, 1997; Jennings et al., 2000; Jennings et al., 2004) have observed an increase in sickness due to added latency whereas other studies (Moss & Muth, 2011; Draper et al., 2001) have failed to confirm the relationship between added latency and sickness. Like Moss and Muth, the current study used an HMD system that did not require the use of a head tracker and hence did not have an inherent low frequency variability in latency in the "0" ms added latency condition. As stated above, it is possible that any studies that employed a head tracker were manipulating both added latency (intentionally) and frequency and amplitude of latency (unintentionally). Our results replicate the findings of Moss and Muth, once again confirming that added latency alone is not the critical

cause of SS in HMDs. It appears that the previous positive findings in this regard may have been due to the results being confounded by either added amplitude or frequency of latency.

Participant Withdrawal

The current study revealed a significant relationship between condition membership and participant withdrawal. A total of 11 participants withdrew out of 120. That's a 9% withdraw rate for the experiment overall. These findings alone are not troubling regarding the use of the HMD, but when the numbers are broken down by condition, the withdraw rate becomes interesting. The baseline condition contained no withdrawals, which was expected. There were 2 withdrawals out of 30 in both the baseline + 200 ms and wave pool conditions which was a withdraw rate of only 7% in each condition. The ocean condition contained the highest number of withdrawals with 7 out of 30 participants, a withdrawal rate of 23%. These withdrawal rates, taken into account with the findings of Fisher's exact test as well as comparisons of sickness experienced by participants in each condition, indicated that participants are far more likely to withdraw as a result of exposure to an HMD with varying amplitude of latency. This condition increases feelings of sickness in participants and motivates a higher number of participants to withdraw. These withdrawal findings support the symptom findings, i.e., the ocean condition produced the most sickness.

Effect of Trial

A repeated measures ANOVA indicated that wearing the HMD and performing the experimental task increased SS. Participants reported experiencing higher levels of SS the longer they were in the HMD. These findings were similar to those found by Moss (2008). However, these findings include participants who dropped-out of the experiment before completion of all experimental trials. Participants were not equally distributed across trials. This is also the reason that peak SSQ scores were used in this experiment to perform comparisons of SS in each condition because not every trial contained the same amount of participants in each condition due to participant withdrawal. Using peak SSQ scores allowed for equal samples to be gathered for each condition regardless of participant withdrawal.

Oculomotor Resting States and Simulator Sickness

The results of this study found changes in oculomotor resting states from pre to post HMD exposure. Further, the changes were not found in any way to relate to peak symptom scores.

No significant differences were expected in dark vergence from pre to post because the displays in the HMD were set according to the IPD of each participant. However, if significant shifts in dark vergence occurred, it was hypothesized that they would be significantly correlated with SS. Paired samples t-tests revealed a significant inward shift for all three measures of dark vergence from pre to post. Shifts in dark vergence were unexpected because the distance between the displays on the HMD was

set according to the IPD of participants. This finding was in conflict to St. Pierre et al. (2011b), which found no shift from pre to post. There are several possible explanations for these shifts.

First, it might be the result of researcher error in IPD settings. In other words, the HMD may have forced participants to view in a slightly more convergent position than their average dark vergence viewing position. The distance between the displays was measured and set manually to the millimeter using a ruler after IPD was measured using an auto-refractometer. In this case, changes in dark vergence could have been due to researcher error in measurement and setting of IPD distance between displays of the HMD. These errors were likely within ± 2 millimeters or less. For this explanation to be true, the error in IPD settings would need to be similar across participants (i.e., IPD set too narrow for participants or IPD set too wide for participants). However, it is unlikely that this error would be consistent across participants.

A second plausible explanation has to do with the accommodation/vergence cross link. An accommodative change has the potential to cause a shift in the vergence system. In this study, a significant shift in dark focus in the left eye occurred as will be discussed below. As dark focus shifted to a closer viewing position, it is possible that the vergence system shifted to a closer viewing situation as well.

A third explanation could be the stability of the HMD on the head of the participants. During the task, the HMD may have shifted ± 1 centimeters with consistent head movements. This possible shift may have forced participants to view the displays from a slightly different angle than the angle they would have started with as a result of

setting the displays to their particular IPD. This, like the previous discussion of researcher error with regard to measuring and setting IPD between the displays in the HMD, is an unlikely explanation because it would also require a consistent shift across participants.

Lastly, this shift could be due to changes in the autonomic nervous system due to sickness. However, these explanations are beyond the scope of the current study. Further research would be required to support these explanations.

Pearson's product moment correlations were performed to determine if there was a correlation between the shifts in dark vergence measurements and SS, but no correlations were observed. These results indicate that there was no relationship between dark vergence shifts and overall SS scores. These results were similar to those found in St. Pierre et al. (2011a; 2011b) in which no significant relationships were found between dark vergence shifts and overall SS.

No significant shift in dark focus was expected in either eye. If shifts in dark focus were observed, it was hypothesized that there would be a significant correlation between SS and the change in dark focus. Analyses of dark focus data revealed a significant inward shift in dark focus in the left eye, but no significant shift in dark focus in the right eye. This finding was unlike the findings of Fowkles et al. (1993) because in the current study, dark focus shift was only observed in the left eye. In addition, the current study observed this shift among all participants whereas Fowkles et al. observed an inward shift in dark focus among only sick participants.

Pearson's product moment correlations were performed to determine if there was a correlation between the shifts in dark focus measurements in each eye and SS, but no correlations were observed. This would indicate that dark focus shifts were not related to overall SS.

Oculomotor Resting States and Simulator Sickness Clusters and Symptoms

The relationships between oculomotor resting states and SSQ cluster and symptom peak scores were assessed using Pearson's product moment correlations. Analyses were performed to determine the relationship between pre and post HMD exposure measures of dark vergence as well as dark vergence change and SSQ cluster and symptom peak scores. No relationships were observed between pre dark vergence measurements and SSQ cluster or symptom peak scores. Significant weak positive correlations were observed between pre dark vergence degrees and MA, and peak stomach awareness scores, indicating that those individuals who started with a closer viewing position reported higher levels of stomach awareness than those participants who had a far starting viewing position. In addition, significant weak positive correlations were observed between the change in dark vergence degrees and MA from pre to post and peak headache scores, indicating that individuals who experienced larger inward shifts in dark vergence reported higher headache scores than those who experienced smaller inward shifts in dark vergence. These findings indicate that although there was no relationship observed between dark vergence and overall SSQ scores, there were relationships between dark vergence and SSQ item peak scores. As theorized by

Howarth and Costello (1997), oculomotor symptomology was related to vergence in the current study. In the current study, the relationship between oculomotor symptoms and dark vergence came in the form of participant reports of headache. This would indicate that a larger inward shift in dark vergence from pre to post may predict the degree to which participants experience headaches. There was no prior research within the HMD literature that indicated how participants would experience individual sickness symptoms as they related to dark vergence. However, there were studies performed regarding near visual work and the relationship between dark vergence and symptoms associated with visual fatigue. Owens and Wolf-Kelly (1987) found that shifts in dark vergence were associated with visual fatigue from the use of a video display terminal (VDT). Tyrrell and Leibowitz (1990) found a correlation between dark vergence prior to and after near visual work using a VDT and participant experience of headaches. The findings from the current study, taken with previous findings of near visual work, indicated that the HMD displays were not scaled correctly to the participant as indicated by symptoms arising from visual fatigue. More simply, the significant shift in oculomotor resting states would not have occurred if the HMD displays were correctly scaled to each participant.

In addition, the more inward dark vergence position of participants was found to be related to participant reports of the stomach awareness item peak scores, which is in the SSQ nausea symptom cluster. This would indicate that dark vergence position prior to HMD use may have the potential to predict participant experience of stomach awareness.

Analyses were performed to determine the relationship between pre and post HMD exposure measures of dark focus as well as dark focus change for each eye and SSQ cluster and symptom peak scores. No relationships were observed between post dark focus measurements or the change in dark focus from pre to post and SSQ cluster or symptom peak scores. Significant weak positive correlations were observed between pre dark focus in the left and right eye and peak fatigue scores, indicating that those individuals who started with a closer viewing position reported higher levels of fatigue than those participants who had a far starting viewing position. A significant weak positive correlation was observed between pre dark focus in the right eye and peak blurred vision scores indicating that participants who started with a closer viewing position in the right eye reported higher levels of blurred vision than those participants who had a far starting viewing position in the right eye. A significant weak positive correlation was observed between pre dark focus in the left eye and peak burping scores indicating that participants who started with a closer viewing position in the left eye reported higher levels of burping than those participants who had a far starting viewing position in the left eye. These findings indicate that although there was no relationship observed between dark focus and overall SSQ scores, it is possible that dark focus could be related to the experience of individual symptoms of SS.

Several relationships were found between dark focus and items on the SSQ. Particularly, relationships were observed between dark focus and the fatigue and blurred vision items on the SSQ which are both in the oculomotor symptom cluster. No previous research in the HMD literature or research on near visual work indicates that a

relationship between dark focus and visual symptoms would have been expected. Owens and Wolf-Kelly (1987) found no relationship between dark focus and the experience of visual fatigue after near work using a VDT. A relationship was also observed between dark focus and the burping item on the SSQ which is in the nausea symptom cluster. These relationships were all found to be positive correlations between dark focus prior to HMD use and these items indicating that dark focus prior to HMD use may have potential to predict these item scores on the SSQ.

Previous research with HMDs gives little to no information regarding the relationship between SSQ symptom clusters and individual symptoms and their relationships to dark vergence or dark focus. St. Pierre et al. (2011b) examined SSQ symptom peak scores and their relationship with dark vergence and dark focus, but the study had a small sample size ($N = 20$). It was thought that with a large sample size, as in the current study ($N = 120$), a little more clarity might be found regarding these relationships. However, the symptoms that seem to have a relationship with oculomotor resting states are those symptoms that reside either in the nausea or oculomotor symptom clusters of the SSQ. It was proposed that oculomotor resting states would be correlated with symptoms in the oculomotor symptom cluster, but it was unknown what other symptoms might be related. Within the near visual work literature, relationships between oculomotor symptoms such as headaches and reports of visual fatigue have been linked to shifts in dark vergence as well as pre and post dark vergence posture (Owens & Wolf-Kelly, 1987; Tyrrell & Leibowitz, 1990). The results from this study indicated that it may be possible to predict the experience of individual SSQ item scores based on the

oculomotor resting states of participants prior to HMD use. In addition, this study also indicates, as does previous research on near visual work, that oculomotor effort should be scaled relative to the dark focus and dark vergence of each participant rather than to an arbitrary far point or to optical infinity.

General Discussion

Designers of VE systems, including HMDs, are faced with the decision to increase system speed or to improve optical realism while managing system costs. The most realistic systems employ increased resolution and detail. However, there is a trade off when making design decisions as enhanced optical realism leads to increased latency (Moss, 2008). Hettinger and Riccio (1992) note that pictorial realism contributes to computational demands, which contributes to latency.

Unfortunately, exposure to latency has the potential to cause SS in users (DiZio & Lackner, 1997; Jennings et al., 2004). Other studies indicate that latency is not the culprit behind the SS problem (Draper et al., 2001; Moss & Muth 2011). Wu et al. (2011) reported that latency is not a constant, but rather it is variable. The variability in latency was associated with head tracker error (low frequency variability) as well as clock asynchronization (high frequency variability). The current study sought to examine the role of this varying error in the experience of SS. The current results support prior findings by Moss and Muth (2011) that added latency by itself does not cause SS. The current study supports the idea that varying amplitude of latency, which is present in systems using head trackers, is related to increased levels of SS. The current study also

partially supports the idea that low frequency of latency, also present in systems using head trackers, may be involved in heightened levels of SS. In addition, SS scores for every condition in the current study were higher than those indicated by Stanney, Kennedy, and Drexler (1997) occurring as a result of exposure to a poorly designed VE.

Limitations and Future Work

The major limitation of this study is the comparison of the frequency of latency conditions in which the baseline and baseline + 200 ms conditions were collapse together then compared to the wave pool and ocean conditions collapsed together. It is not entirely clear if the difference in sickness scores (i.e., SSQ peak and MSAQ scores) were higher in the 0.2 Hz condition because of the 0.2 Hz frequency or because of the presence of the varying amplitude of latency. A one-way ANOVA found a significant main effect for the latency manipulation (i.e., added latency, amplitude of latency, and frequency of latency). However, Fisher's LSD indicated that the only condition that significantly differed from any other was the ocean condition, which significantly differed from every other condition. This could potentially indicate that the significant difference found for frequency of latency conditions is a frequency of latency by amplitude of latency interaction.

Another limitation was the basis for which potential participants were excluded from participation in the study with regard to screening for MS. Participants completed the MSHQ to gauge their susceptibility to MS. Individuals who reported the experience of MS symptoms frequently or easily were excluded from the study. This is a limitation

for a couple reasons. First, reports of prior MS experience were subjective. However, no objective measure of MS was available. Secondly, the current study excluded participants who might be prone to MS. Participants who experience MS more frequently or easily might yield differing results. Including these participants might have yielded more extreme scores or larger differences between conditions.

A between-subjects design was used in the current study. This is a limitation because it is possible that individual differences may have influenced the findings of the experiment because of error variance. This design was used because of time constraints, possible participant dropout, and habituation effects. It is unlikely that the design for the current study affected the findings because the participants were randomly assigned to each condition, the number of males and females were evenly distributed in each condition, and the large sample size in each condition.

A within-subjects design might be a good approach for future research. This may eliminate any individual differences that might be present thereby reducing error variance. In this design, each participant will experience each condition. This will eliminate error variance due to subject-related factors. This would assure that any differences in scores or performance across conditions cannot be due to error variance that might arise from such differences such as in the case of a between-subjects design. Within-subjects design is more powerful (i.e., more sensitive to the effects of manipulations of the independent variable) than an equivalent experiment using a between-subjects design due to reduced error variance.

Future research where manipulation of amplitude of latency and frequency of latency are present may benefit from a repeated measures design that can test main effects of frequency of latency and amplitude of latency as well as examining the interaction between frequency and amplitude of latency. This should be performed because in typical head-tracked HMD system configurations, frequency and amplitude of latency do not exist independently of each other. This design will assist in untangling the frequency of latency and amplitude of latency factors. This could be performed using a simple 2X2 within-subjects factorial design (See Figure 5.1.).

		Frequency of Latency	
		0.2 Hz	1.0 Hz
Amplitude of Latency	20-100 ms (fixed)		
	20-100 ms (varying)		

Figure 5.1. 2X2 within-subjects factorial design for future research involving amplitude and frequency of latency manipulations.

In the above design, frequency of latency can never be set to 0 Hz in the presence of amplitude of latency because of their lack of independence. Amplitude of latency can be manipulated in two ways. First, it can be manipulated to either be fixed or varying as in the above example. In this case, the number in ms should be the same in each condition and whether or not the latency is fixed or varying should be manipulated.

Second, alternatively to the above design, amplitude of latency should be fixed in all conditions or varying in all conditions while the actual amplitude of latency in ms should have two different manipulations. An example would be conditions in which amplitude of latency would be either high or low. Specifically, high amplitude could be 20-100 ms and low amplitude of latency could be 10-20 ms.

Future research with HMDs, sickness, and oculomotor resting states may benefit from multiple manipulations of display distance (i.e., displays set to the IPD of participant, displays set closer or farther away than the IPD of the participant). This would allow for an analysis of sickness based on different display settings. It would shed light on how SS and its various symptom profiles occur when dark vergence shifts inward, outward, or remains the same from pre to post exposure to an HMD. With displays set closer together, it would force an inward dark vergence shift among participants. This would allow for study of the relationship between inward shifts in dark vergence and SSQ scores, SSQ cluster scores, and SSQ item scores. Displays set farther away from each other would force an outward dark vergence shift among participants. This would allow for study of the relationship between outward shifts in dark vergence and SSQ scores, SSQ cluster scores, and SSQ item scores. Future research into these oculomotor resting states and the experience of SSQ scores should focus on what symptomology is associated with different shifts (i.e., inward or outward).

Conclusion

The primary goal of this study was to examine the role of latency in HMD generated SS. The current study presents strong evidence indicating that SS is at least to some degree the result of fluctuations in the amplitude of latency inherent within some HMD systems, specifically those projecting true VEs because they utilize head trackers. The finding that varying amplitude of latency causes significantly higher levels of sickness than the fixed amplitude of latency condition addresses the primary purpose of this study. The finding that 0.2 Hz frequency of latency conditions taken together causes significantly higher levels of sickness compared to the 0 Hz frequency of latency conditions together addresses the primary purpose of this study, but the significance of frequency of latency to sickness is still somewhat unclear due to the fact that the only condition which differed significantly from the others was the one in which both frequency and amplitude of latency were manipulated. Future research needs to examine effects of frequency and amplitude of latency conditions and the interaction between the two. This can be examined using a within-subjects design as discussed above.

The secondary goal of this research was to determine the relationship between changes in the visual system due to HMD use and their relationship with the propensity to experience sickness. Significant differences between oculomotor resting states prior to and after HMD use were observed. In addition, only weak positive correlations were present between oculomotor resting states and SSQ symptom peaks. This did not fully address the secondary goal of the current study. Future research with multiple display IPD settings may provide much clearer information regarding what SSQ symptomology

is associated with different oculomotor shifts (i.e., inward or outward). In addition, the current study supports the notion from prior research on near visual work (Owens & Wolf-Kelly, 1987; Tyrrell & Leibowitz, 1990) that oculomotor effort should be scaled relative to the oculomotor resting states of participants as opposed to an arbitrary far point or optical infinity.

The current study offers important insight into minimizing the experience of SS while wearing an HMD. The varying amplitude and frequency of latency is found in systems using head trackers. According to Wu et al., (2011), these systems yield varying low frequency oscillations from 0.5-1.0 Hz with varying amplitude from 20-100 ms. This frequency range has been noted by many studies (Alexander et al., 1947; O'Hanlon & McCauly, 1974; Lawther & Griffin, 1988; Duh et al., 2004) as being the cause of nausea in vertical motion situations. The range of 0.2-1.0 Hz has been found by several studies (Golding & Markey, 1996; Golding et al., 1997; Golding et al., 2001) to cause motion sickness in horizontal motion situations. The current study supported the notion that variability in amplitude of latency is to some degree responsible for the experience of SS. In addition, the current study also indicates that there is a possibility that fluctuations of frequency of latency may also to some degree be responsible for the experience of SS. With this in mind, an effort should be made in the design of HMDs to minimize the drift in sensor error that causes these fluctuations to be present. The minimization of the drift in sensor error could allow for the use of HMD with lower risk of the experience of SS symptomology.

Although there are other factors associated with SS in HMD VE systems, the current study shines light on factors that had not yet been researched with regard to SS. Variability in frequency and amplitude of latency may have been present in many studies regarding SS in the past. These factors may have caused SS in participants unbeknown to the researcher. Past studies using head tracked HMDs (Wildzunas et al., 1996; DiZio & Lackner, 1997; Jennings et al., 2000; Jennings, et al., 2004) may have found a relationship between latency and SS, but were unknowingly examining the role of frequency and amplitude of latency regarding the experience SS. This may indicate that previous research regarding latency in an HMD using head trackers and the experience of SS should be reviewed carefully and critically because of the possibility of important factors (i.e., frequency and amplitude of latency) that may not have been controlled.

APPENDICES

Appendix A

Consent Form

Information about Being in a Research Study
Clemson University

Effects of Helmet-Mounted Display Characteristics on User Experience

Description of the Study and Your Part in It

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

Your part in the study will be to

1. Sit in the dark to adapt your eyes to darkness.
2. Between measurements, you will be asked to wear a blindfold for brief time periods.
3. Have the distance between your 2 eyes measured.
4. View points of light, presented by the Vergamatic II, in the dark and reporting whether or not you see the points. The Vergamatic II presents a stimulus using light emitting diodes (LED). The Vergamatic II measures the natural resting position of your eyes.
5. Have the natural resting focus of your eyes measured. This measurement is taken using an eye doctor's tool called an Auto Refractometer. The Auto Refractometer is an optometric tool that assesses if you focus close up or far away.
6. Wear 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.
7. Make a series of timed head movements as you view various objects located in either the real or simulated world that you are looking at.
8. Complete 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 and 45 minutes to complete this study. You may be asked to return to complete this study multiple times if you are willing.

Risks and Discomforts

There are certain risks or discomforts that you might expect if you take part in this research. They include none/some/all of the following symptoms: dizziness, weakness, nausea, headache, vomiting. These symptoms will go away when the HMD is removed.

Possible Benefits

We do not know of any way you would benefit directly from taking part in this study.

However, this study may 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.

Incentives

By participating in this study, you may receive a monetary payment or course extra credit. Note, the same course/extra credit is available for a non-research activity that involves the same effort and time investment (see your course instructor for more information on credit alternatives).

Protection of Privacy and Confidentiality

We will do everything we can to protect your privacy and confidentiality. We will not tell anybody outside of the research team that you were in this study or what information we collected about you in particular. 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.

We might be required to share the information we collect from you with the Clemson University Office of Research Compliance, the federal Office for Human Research Protections and/or the Office of Naval Research. If this happens, the information would only be used to find out if we ran this study properly and protected your rights in the study.

Choosing to Be in the Study

You do not have to be in this study. You may choose not to take part and you may choose to stop taking part at any time. You will not be punished in any way if you decide not to

be in the study or to stop taking part in the study. If you decide not to take part or to stop taking part in this study, it will not affect your grade in any way.

If you choose to stop taking part in this study, the information you have already provided will be kept in a confidential manner.

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 in this research study, please contact the Clemson University Office of Research Compliance (ORC) at 864-656-6460 or irb@clemson.edu. If you are outside of the Upstate South Carolina area, please use the ORC's toll-free number, 866-297-3071.

Consent

I have read this form and have been allowed to ask any questions I might have. I agree to take part in this study.

Participant's signature: _____ Date: _____

A copy of this form will be given to you.

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 medications?	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 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 question 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

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					
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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					
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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					
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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					
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Appendix F

Histograms of Peak SSQ Scores by Condition

Figure F-1. Frequency distribution of peak SSQ scores for baseline condition.

Figure F-2. Frequency distribution of peak SSQ scores for baseline + 200 ms condition.

Figure F-3. Frequency distribution of peak SSQ scores for wave pool condition.

Figure F-4. Frequency distribution of peak SSQ scores for ocean condition.

Appendix G

Histograms of MSAQ Scores by Condition

Figure G-1. Frequency distribution of MSAQ scores for baseline condition.

Figure G-2. Frequency distribution of MSAQ scores for baseline + 200 ms condition.

Figure G-3. Frequency distribution of MSAQ scores for wave pool condition.

Figure G-4. Frequency distribution of MSAQ scores for ocean condition.

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 baseline condition.

Figure H-2. Frequency distribution of square root peak SSQ scores for baseline + 200 ms condition.

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

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

Appendix I

Histograms of the Square Root Transformations of MSAQ Scores by Condition

Figure I-1. Frequency distribution of the square root MSAQ scores for baseline condition.

Figure I-2. Frequency distribution of the square root MSAQ scores for baseline + 200 ms condition.

Figure I-3. Frequency distribution of the square root MSAQ scores for wave pool condition.

Figure I-4. Frequency distribution of the square root MSAQ scores for ocean condition.

Appendix J

Histograms of Dark Vergence Degrees Pre and Post

Figure J-1. Frequency distribution of dark vergence degrees prior to HMD use.

Figure J-2. Frequency distribution of dark vergence degrees after HMD use.

Appendix K

Histograms of Dark Vergence Meter Angle Pre and Post

Figure K-1. Frequency distribution of dark vergence meter angle prior to HMD use.

Figure K-2. Frequency distribution of dark vergence meter angle after HMD use.

Appendix L

Histograms of Dark Vergence Distance in Meters Pre and Post

Figure L-1. Frequency distribution of dark vergence distance in meters prior to HMD use.

Figure L-2. Frequency distribution of dark vergence distance in meters after HMD use.

Appendix M

Histograms of Dark Vergence Change from Pre to Post

Figure M-1. Frequency distribution of the change in dark vergence degrees from pre to post.

Figure M-2. Frequency distribution of the change in dark vergence meter angle from pre to post.

Figure M-3. Frequency distribution of the change in dark vergence distance in meters from pre to post.

Appendix N

Histograms of Dark Focus of the Left Eye Pre and Post

Figure N-1. Frequency distribution of dark focus for the left eye prior to HMD use.

Figure N-2. Frequency distribution of dark focus for the left eye after HMD use.

Appendix O

Histograms of Dark Focus of the Right Eye Pre and Post

Figure O-1. Frequency distribution of dark focus for the right eye prior to HMD use.

Figure O-2. Frequency distribution of dark focus for the right eye after HMD use.

Appendix P

Histograms of the Change in Dark Focus from Pre to Post

Figure P-1. Frequency distribution of the change in dark focus of the left eye from pre to post.

Figure P-2. Frequency distribution of the change in dark focus of the right eye from pre to post.

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