8-2014

THE EFFECT OF 0.2 HZ AND 1.0 HZ FREQUENCY AND 100 MS AND 20 - 100 MS AMPLITUDE OF LATENCY ON SIMULATORY SICKNESS IN A HEAD MOUNTED DISPLAY

Amelia Kinsella
Clemson University, akinsel@g.clemson.edu

THE EFFECT OF 0.2 HZ AND 1.0 HZ FREQUENCY AND 100 MS AND 20 – 100 MS AMPLITUDE OF LATENCY ON SIMULATORY SICKNESS IN A HEAD MOUNTED DISPLAY

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Masters of Science
Applied Psychology

---

by
Amelia J. Kinsella
August 2014

Accepted by:
Dr. Eric Muth, Committee Chair
Dr. Adam Hoover
Dr. Chris Pagano

ABSTRACT

The purpose of the current experiment was to contribute to the existing literature on the relationship between frequency of latency and amplitude of latency and simulator sickness experienced in a head mounted display (HMD). Motion sickness has been studied for decades in a variety of vehicles including ships, planes, trains and automobiles. More recently virtual environments, including those utilizing an HMD have been shown to generate significant sickness, often termed simulator sickness. Many studies have linked system latency to simulator sickness and recent research has found that with current technology latency is not a constant; but rather it varies systematically over time due to sensor errors and clock asynchronization. One hundred twenty participants were recruited and randomly assigned to one of four conditions (0.2 Hz frequency of latency with 100 ms fixed amplitude of sinusoidal latency; 0.2 Hz frequency of latency with 20 – 100 ms varying amplitude of sinusoidal latency; 1.0 Hz frequency of latency with 100 ms fixed amplitude of sinusoidal latency; 1.0 Hz frequency of latency with 20 – 100 ms varying amplitude of sinusoidal latency). Collected data were analyzed using analysis of variance. A main effect of frequency of latency was found, and data trended toward a main effect of amplitude of latency. Participants reported greater sickness in 0.2 Hz frequency conditions and in the 1 Hz varying amplitude condition, indicating both frequency and amplitude of latency contribute to simulator sickness and are important factors to consider in regard to system latency. In conclusion, both frequency and amplitude of latency play an important role in simulator sickness.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Eric Muth for his support and guidance during this experiment. I would also like to thank Dr. Adam Hoover and Dr. Chris Pagano for being on my committee and assisting me through this process. I want to thank Ryan Mattfeld for creating the update delay program, his help validating the program, and his assistance with MATLAB throughout this project. I thank my fellow lab mates Phil Jasper, James Salley, and Mike Wilson for standing by me throughout data collection as well as the members of our Creative Inquiry team, especially Lauryn Nana and Lauren Brown, for assisting me with data collection and analysis. Finally, I would like to thank my parents and Zach Shell for their love, support, and encouragement during this process.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

INTRODUCTION

Purpose

The purposes of this study were: 1) to examine the sickening effects of oscillations with fixed and varying amplitude of display latency within an HMD at the 0.2 Hz and 1.0 Hz frequencies and 2) to further examine the interaction effects of frequency and amplitude of latency on the occurrence of simulator sickness.

Motion Sickness and Simulator Sickness

Motion sickness has been a well-known and well-documented problem for hundreds of years, dating back to Greek scholars twenty-five centuries ago, and mentioned by Hippocrates, Julius Caesar, Lawrence of Arabia, Charles Dickens, and Admiral Nelson (Lawther & Griffin, 1986; Money, 1972). Despite years of study, motion sickness continues to be a problem today. The most common symptoms associated with motion sickness are vomiting, sweating, salivation, apathy, fatigue, stomach awareness, disorientation, dizziness, and incapacitation (Kennedy, Drexler, & Kennedy, 2010). The most widely accepted theory explaining motion sickness is the sensory conflict theory (Reason & Brand, 1975; Oman, 1990).

Similarities between oscillations in real and simulated motion. Bijveld et al. (2008) directly compared real and simulated motion and how they relate to sickness using an off vertical axis rotation paradigm. They found that simulated motion is less nauseogenic than actual motion in both sickness rating and time to sickness. They also identified the three most common symptoms for real motion to be bodily warmth, stomach awareness, and nausea and the three most common for simulated motion were

headache, dizziness, and nausea. They found a significant difference in headache rating and noted that nausea was common among both real and simulated motion.

Sensory conflict theory. Reason and Brand (1975) introduce sensory conflict theory as a contradiction between information processed through the visual system and input received from the vestibular system (Emmerik, Vries, & Bos, 2011). The nervous system receives conflicting information and motion sickness results. Sensory conflict theory is used to explain when there is interference in inductive inferences made by animals as they interact with the world. These interferences are thought to lead to motion sickness.

Reason (1978) explains two components of sensory conflict theory. First, all situations producing motion sickness can be described as a condition in which motion perceived by the eyes, vestibular system, and non-vestibular proprioceptors differ from each other. Second, in order for motion sickness to occur, the vestibular system must be involved, either directly or indirectly. Both of these components are involved in perceiving conflicting information from different sensory systems, resulting in motion sickness.

The vestibular system. The vestibular system and the visual-vestibular interaction both play a key role in experiencing motion sickness and simulator sickness. Each ear contains a vestibular apparatus located in the bony labyrinth of the inner ear. The vestibular apparatus is used to sense head movements and react to them via response signals. These response signals aid in eye movements, posture and balance, and perception of motion and orientation (Stoffregen, et al., 2002). The vestibular apparatus

is crucial for everyday functioning, including, but not limited to standing, walking and reading.

The body has a vestibulo-ocular reflex that aids in vision during head movements by stabilizing images on the retina during head motion. When the head moves, the vestibular apparatus senses the acceleration and deceleration and signals the oculomotor system, providing information about direction and rate of movement. Then the oculomotor system compensates for the movement with eye movements in the opposite direction of the head movement. Discrepancies between information from the vestibular apparatus and the visual system (i.e. visual-vestibular interactions) can cause conflict between what the body feels and what the body sees, which can result in discomfort and motion sickness.

Virtual Environments and Head Mounted Displays

Virtual Environments. Virtual environments simulate human perceptual experience by creating an impression of something that is not there in reality (Carr, 1995). They are often used to advance fields such as medicine, engineering, education, design, training, and entertainment (Stanney, Mourant, & Kennedy, 1998). Virtual environments can be used for training through simulation when on-the-job training is too risky. Training with virtual environments instead of on-the-job can possibly prevent loss of money, equipment, or health of workers. When dealing with highly trained professionals (e.g. warfighters or aviators), there are many benefits for using virtual environment HMD technologies for training or rehearsal (Gorman, 1990; Sowndarajan, Wang, & Bowman, 2008). These technologies have the ability to create various

dangerous and stressful scenarios for the trainee without having them endure the real life consequences of the situation such as poor performance, injury, or death.

Head Mounted Displays. Head mounted displays (HMDs) are head-worn personal display units used to view a real world scene or a virtual environment. They are made up of a helmet with an individual display or pair of displays consisting of small CRTs or liquid-crystal displays (LCDs). HMDs can be monocular (projecting an image into a single display), binocular (projecting disparate images through individual displays for each eye), or bi-ocular (projecting identical images to both eyes through two displays). Typically, HMDs have head tracking capabilities to track the user's visual point of reference within the virtual environment. Head tracking works to constantly update the visual display as the user moves with the HMD. The head tracker monitors the user's head movements and sends the user's position in space back to the computer. The computer then processes the information and updates the visual display viewed by the user so the display matches the position of the user's head.

HMDs and simulator sickness. Exactly why HMD generated virtual environments make people sick is unknown. Hypothesized factors include the discrepancy of the display from the real world, system lag, narrow field of view, low display resolution, and fidelity within HMDs. Field of view in HMDs is much smaller than the 360° field of view in the real world, and even smaller than the 180° - 200° field of view in humans (Toet, Jansen & Delleman, 2007). A smaller field of view necessitates larger head movements while wearing the HMD. Resolution is also diminished from the real world, resulting in low quality image displays. Generally, there is a tradeoff between

weight, resolution and/or field of view. The fidelity of the simulation also plays a role in the discrepancy between the real world environment and the display within the HMD. While high fidelity images can lessen this discrepancy, there is also evidence that higher fidelity HMDs increase symptoms of simulator sickness (Kennedy, Hettinger, & Lilenthal, 1990).

System lag (also called display update delay or end-to-end latency) is innate in HMDs and another possible cause of sickness. Lag can be defined as the duration between a head movement and the time it takes the display to update. System lag in an HMD can cause visuo-vestibular conflicts. These conflicts are similar to those predicted in Reason & Brand's sensory conflict theory of motion sickness (Reason & Brand, 1975).

Several studies have looked at simulator sickness in HMD generated virtual environments. In a study by Howarth and Costello, participants reported a significantly greater amount of simulator sickness symptoms after using an HMD than after using a visual display unit (Howarth & Costello, 1997). These results were explained by sensory conflict theory due to visuo-vestibular conflicts that occur while using an HMD. A more recent study looked at simulator sickness while using an HMD to capture real world video scenes (as opposed to a virtual environment; Moss, Scisco, & Muth, 2008). It was found that peak sickness scores were significantly higher while wearing the HMD to view a real world scene compared to not wearing the HMD.

System latency. System latency is innate in the system and described by the time it takes to update the system from initial movement to actuation (e.g., the time it takes to sense a head movement, process the movement, and actuate an update event of the visual

scene in the display). Latency can also be defined in terms of display delay, which is the sum of all temporal delays between the system input and the output of the visual scene displayed in the HMD (Moss, et al., 2011). These delays could be due to many things including (but not limited to) processing times, transport times, update rates, and clock asynchronicity.

System latency is generally in the tens to hundreds of milliseconds (Wu, Dong, & Hoover, 2013). Despite the small range, the latency is prominent enough to be sensed by humans in certain situations (Moss, et al., 2010).

Because system latency occurs on the millisecond scale, it is challenging to measure. While it can be measured both internally and externally, measuring it internally does not include the time data may spend in buffers, time spent by the sensor to acquire data, or time spent by the actuator to output data. Therefore, it is preferred to measure latency externally using a so-called outside observer method. There are two ways to measure latency externally. First, a camera can be used to continuously monitor the system; second, event-driven instrumentation can be used to measure discrete events (Wu, Dong, & Hoover, 2013). As it has been found that latency is not constant, but rather varies continuously, the preferred method is the continuous camera monitor.

Latency is a characteristic of human sensory processing that follows from the vestibular-ocular reflex (VOR) that occurs during head movements. VOR is used to stabilize the visual environment on the retina and consists of compensatory eye movements that occur in the opposite direction of the head movement. It has been calculated that the average latency of the VOR is 8.6 ms (Collewijn & Smeets, 2000).

Many studies have looked at the human perceptual threshold for system latency, and results have varied. A 2010 study examined human perceptual threshold for lag using a rotating chair and optokinetic drum paradigm (Moss, et al., 2010). Results from this study showed a lag threshold of 147.64 ms ± 84.91 ms. Other experiments using HMDs to determine lag thresholds have varied greatly from 14.3 ms – 245 ms (Allison, et al., 2001; Ellis, et al., 2004; Ellis, et al., 1999; Ellis, et al., 1999). Due to the varying results of previous studies, the human lag threshold may fluctuate based on HMD application as well as user characteristics such as experience level with HMDs (Moss, et al., 2010).

Some researchers theorize technological limitations such as update delay, fidelity, field of view, and resolution, in HMDs lead to simulator sickness (Kennedy, Hettinger, & Lilienthal, 1990; Pausch, Crea, & Conway, 1992), and even though many technological advances are being made, simulator sickness is still prevalent (Kennedy, et al., 2003). Further research needs to be completed to have a better idea of what the causal factors of simulator sickness actually are.

Latency and Simulator Sickness. System latency is a common problem in HMDs because it is linked to simulator sickness. Lag (a specific type of system latency) is the time between head movements and the resulting movement in the visual display and is linked to simulator sickness in an HMD (DiZio & Lackner, 1997). Display delays cause a temporal mismatch between head movement and scene movement and have been found to increase the likelihood of simulator sickness (Draper, et al. 2001).

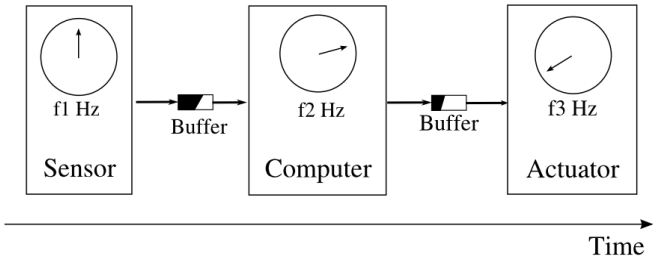


Figure 1.1: Typical configuration with components operating on independent clocks causing non-constant latency in the system (From Wu et al., 2013).

System latency confounds pointing and object location tasks (Teather, et al., 2009), catching tasks (Lippi, et. al, 2010), and ball bouncing tasks (Morice, Siegler, & Bardy, 2008). It has also been found that higher fidelity images produce increased system latency (Hettinger & Riccio, 1992). In the past, latency was thought of as a constant, but recent research has shown that latency can vary over time (Wu, Dong, & Hoover, 2013; Moss & Muth, 2011). It is probable that the *variability* of latency, specifically amplitude of latency, leads to increased simulator sickness (St. Pierre, 2012).

Frequency and Amplitude of Motion. Originally, motion sickness research focused on transportation motion and involved movement from land vehicles, ships, and aircraft. Most researchers focused on the vertical heave motion often experienced while on a boat or ship and many studies concluded peak levels of nausea occurred while experiencing motion with frequencies less than 1.0 Hz (Alexander, et al., 1947; O'Hanlon & McCauley, 1974; Lawther & Griffin, 1988; Duh, et al., 2004). Figure 2 shows a plot of the motion sickness model by frequency and acceleration based on O'Hanlon and McCauley's findings with their motion generator. In O'Hanlon and McCauley's study on motion sickness, 308 participants sat in a motion generator with 14 conditions for up to

two hours. It was found that frequencies around 0.2 Hz had the highest motion sickness incidence, with 0.167 Hz being the most nauseogenic. Conversely, results also showed that humans are able to tolerate higher accelerations at higher frequencies (0.5 – 1 Hz). From this study, a preliminary model of motion sickness was able to simultaneously link incidence of motion sickness to the frequency and acceleration parameters of vertical periodic motions and a curvilinear relationship was shown between wave frequency and motion sickness incidence. O'Hanlon and McCauley provided evidence that frequency is a critical factor in vertical heave motion and the incidence of motion sickness.

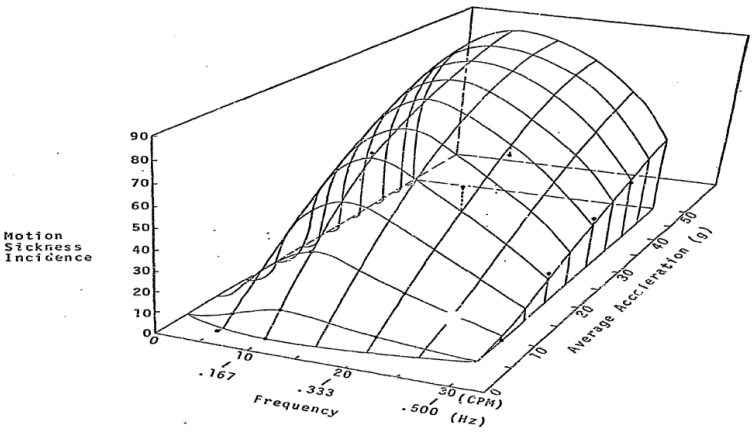


Figure 1.2: Relationship of MS to wave frequency and average acceleration (From O'Hanlon & McCauley, 1974)

After early research of the effect of vertical heave motion on sickness symptoms, many experiments were conducted to examine the effects of frequency on horizontal motion. Golding, Phil, and Markey (1996) conducted a study to examine how frequency affects motion sickness on linear oscillations in the horizontal direction. They looked at 0.205, 0.35, and 0.5 Hz frequencies of motion and their effect on motion sickness. The upper frequency of 0.5 Hz was chosen under the assumption that sickness would decline

at higher frequencies for horizontal motion, as it did with vertical motion. Results from this study confirmed that frequency of motion affects motion sickness with horizontal oscillations in a similar way as with vertical oscillations. It was found that nauseogenicity of motion increased and time to sickness significantly decreased at lower frequencies, with time to sickness in the 0.205 Hz condition being significantly less than in the other two conditions.

Later studies by Golding and colleagues had similar findings when looking at different frequency conditions. When looking at frequencies between 0.35 – 1.0 Hz, a significant effect was found with sickness increasing as frequency decreased (Golding et al., 1997). Specifically, they found time to sickness was significantly less in the 0.35 Hz condition than in the higher conditions. They concluded that with horizontal oscillatory motion, the nauseogenic potential is significantly reduced at frequencies above 0.5 Hz and continues to lessen all the way up to 1.0 Hz. From these results Golding et al. also concluded that the frequency component is central to the nauseogenicity of linear motion.

After the two previous studies, Golding, et al. examined the frequencies above and below the most nauseogenic frequency of 0.2 Hz (Golding et al., 2001). In this experiment, 0.1, 0.2, and 0.4 Hz frequencies were examined and it was found that nauseogenicity of motion is greatest at frequencies around 0.2 Hz and significantly decreases above and below. They found time to sickness was significantly less in the 0.2 Hz condition than the 0.1 and 0.4 Hz conditions. They also found that more subjects reached the maximum level of nausea before the maximum time of the study in the 0.2 Hz condition than the other two conditions. Another study examining horizontal motion

by Donohew & Griffin (2004) was conducted to examine the effect of lateral oscillation on motion sickness at frequencies between 0.0315 – 0.2 Hz. In this experiment, subjects exposed to the higher frequencies (0.16 – 0.2 Hz) experienced more symptoms and gave significantly higher ratings for sickness symptoms than those exposed to frequencies below 0.16 Hz. No significant difference was found between 0.16 – 0.2 Hz frequencies. These results contribute to previous conclusions that frequency of motion is fundamental to incidence of motion sickness, as well as the conclusion that humans are highly susceptible to motion sickness around 0.2 Hz.

A study to determine the nauseogenicic effects of tilt, exposure duration and frequency for the optokinetic equivalent of off vertical axis rotation also found 0.2 Hz frequency to yield the highest sickness symptoms (Goulding, et al., 2009). The authors speculated that the 0.2 Hz frequency may be a causal mechanism that evokes sickness in widely differing stimuli. In other words, while many different types of stimuli may contribute to symptoms of motion sickness, perhaps one common trait among these stimuli is the 0.2 Hz frequency of motion.

Frequency and amplitude of latency. There are two main components of latency fluctuation: frequency of latency and amplitude of latency. Wu, Dong, & Hoover (2013), recently found that latency is variable and changes due to a drift in sensor error. They found the drift to be within the range of 0.5 to 1.0 Hz with measured oscillations in amplitude of around 20-100 ms. Frequency of latency refers to the rate at which the latency changes, measured in cycles per second (Hz). Amplitude of latency refers to the range of time the image is lagging behind. Figure 3 depicts latency at both constant

frequency and constant amplitude and figure 4 shows constant frequency of latency with varying amplitude of latency.

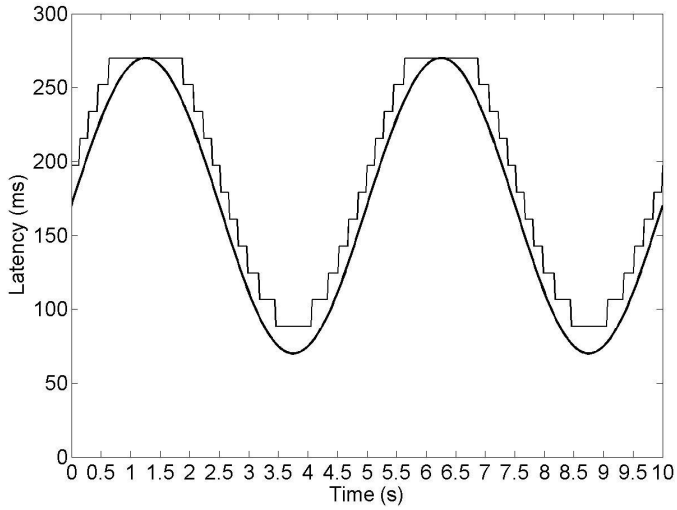


Figure 1.3: Latency with 0.2 Hz frequency and 100 ms amplitude.

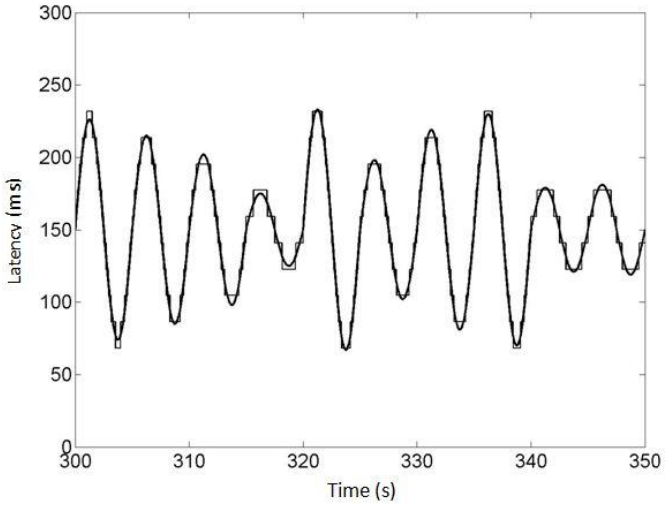


Figure 1.4: Latency with 0.2 Hz constant frequency and amplitude varying from 20 – 100 ms.

Just as frequency and amplitude of motion are thought to be fundamental to motion sickness, frequency and amplitude of latency are thought to be fundamental in

simulator sickness. It has been hypothesized that sickness in these two domains may have a similar relationship with frequency, namely that sickness is maximized around 0.2 Hz frequency. However, there has been some discrepancy in the previous research on the frequency of maximum nauseogenicity for simulator sickness and only a limited amount of frequencies have been tested. Duh et al. (2004) identified a "cross-over frequency" of 0.06 Hz, which they defined as the visual and vestibular self-motion systems is maximum. The cross-over frequency occurs due to conflicting visual and vestibular self-motion cues and they claimed it has the highest potential for simulator sickness. Unlike that of real motion, Duh and colleagues claim that the most nauseogenic frequency for simulated motion is 0.06 Hz instead of 0.2 Hz. However, this theory was never tested with a purely visual stimulus.

Recently, Diels and Howarth (2013) conducted a study to examine the effect of frequency on simulator sickness using a purely visual stimulus. They included frequencies between 0.025 and 1.6 Hz, and contrary to Duh et al.'s claims, they identified humans to be highly susceptible to sickness when the frequency is between 0.2 – 0.4 Hz. Results from Diels and Howarth's study showed increasing sickness with increasing frequency for the range of 0.025 – 0.2 Hz and decreasing sickness with increasing frequency for the range of 0.2 – 1.6 Hz. They also found that 0.2 Hz yielded higher sickness ratings and shorter times to sickness than the other frequencies.

These results indicate that humans are sensitive to 0.2 Hz frequency for both real and simulated motion and demonstrate the similarity in sickness patterns for both real and

simulated motion, where nauseogenicity occurs around 0.2 Hz and steadily decreases at frequencies above 0.2 all the way to 1.6 Hz.

Both frequency and amplitude of motion were examined in St. Pierre's 2012 study. This study looked at the effect of added latency, frequency of latency, and fixed and varying amplitude of sinusoidal latency on simulator sickness. The results from this experiment showed that 0.2 Hz was most sickening with latency varying from 20 – 100 ms. These results agree with Diels and Howarth's finding that humans are highly susceptible to sickness around 0.2 Hz for both real and simulated motion. It also emphasizes the involvement of varying amplitude of latency and its effect on simulator sickness.

Latencies that vary over time are being examined and compared to latencies that remain constant over time. All latencies in this paper are written as latency(t) = A sin(2 pi f t) + K + B, where B is the existing system baseline. This formula can be used to describe both constant and sinusoidally varying latencies. If f = 0 or A = 0 then the latency is constant; otherwise the latency varies sinusoidally over time. Latency is referred to by providing values for (A, f, K, B). For example, a latency of (A = 0, f = 0, K = 130 ms, B = 70 ms) refers to a constant latency of 200 ms. A latency of (A = 50 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms) refers to a sinusoidal latency with a baseline of 170 ms, amplitude of 50 ms and frequency of 0.2 Hz. Note that the baseline must always be larger than the amplitude because we do not consider cases where the latency can be negative. We also study latencies where the frequency and amplitude are varied period to period. We denote these by providing a range for A and/or f. For example, a latency of

(A=20-100 ms, f=0.2 Hz, K=120) denotes a latency that changes amplitude to a random value between 20-100 ms at the start of each period. To ensure clarity, all latencies will henceforth be described by providing values or ranges for (A, f, K).

Frequency and Amplitude of Motion and Their Relationship to Motion Sickness

A recent study looked at different conditions of frequency of latency and amplitude of latency within an HMD to see which would be most sickening (St. Pierre, 2012). Four conditions were tested: (A = 0, f = 0, K = 0 ms, B = 70 ms), (A = 0, f = 0, K = 200 ms, B = 70 ms), (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms), and (A = 20 – 100 ms, f 0.2 Hz, K = 100 ms, B = 70 ms). Participants were required to complete an object location task that required them to make head movements to find different objects around the room while wearing an HMD. A significant increase in simulator sickness symptoms was found in varying amplitude conditions compared to fixed amplitude conditions. This finding implies that the varying amplitude is the cause for increased simulator sickness symptoms. However, varying amplitude was only examined with the known nauseogenic 0.2 Hz frequency, confounding the amplitude and frequency effects. If it truly was the varying amplitude that caused sickness, then varying amplitude of latency on its own (without being combined with 0.2 Hz frequency) should result in increased sickness symptoms. This idea needs to be further investigated so the role of frequency of latency and amplitude of latency in simulator sickness can be fully understood.

Present Study

The purpose of the present study was to further examine the interaction between frequency and amplitude of latency within an HMD. Specifically, the relationship between frequency of latency and increased simulator sickness was assessed. The Applied Human Psychophysiology Laboratory at Clemson University has been looking at the effects of HMDs on simulator sickness. In 2008, effects of update delay, image scale factor, and peripheral vision on simulator sickness were examined (Moss, 2008). Marginal support was found for 200 ms update delay increasing simulator sickness in participants. Wu, Dong, and Hoover (2013), also from Clemson University, then found a new way to continuously measure end to end latency and discovered that update delay, or latency, in HMDs in not constant, but variable. They hypothesized that this variable latency contributes to the simulator sickness when using an HMD. In 2012, St. Pierre looked at both constant offset and variable latency in HMDs and their relationship to simulator sickness. He found variable latency resulted in significantly higher sickness scores than constant offset. He also found partial support for both 0.2 Hz frequency and varying amplitude of sinusoidal latency causing increased sickness scores. The current study further explored frequency and amplitude of latency in an HMD. A known sickening frequency (f = 0.2 Hz), and a known non-sickening frequency (f = 1.0 Hz) were coupled with fixed amplitude of sinusoidal latency (A = 100 ms) and varying amplitude of sinusoidal latency (A = 20 – 100 ms) to further explore their relationship to simulator sickness.

As previously discussed, St. Pierre (2012) recently found a relationship between amplitude of latency and simulator sickness. However, the relationship between frequency of latency and simulator sickness has not been fully investigated. Therefore, the frequency component of latency in HMDs needs to be assessed further to completely explore the relationship between frequency of latency and simulator sickness in HMDs. To do this, a known nauseogenic frequency of latency (f = 0.2 Hz) and a known less nauseogenic frequency of latency (f = 1.0 Hz) were used along with fixed amplitude of sinusoidal latency (A = 100 ms) and varying amplitude of latency (A = 20 – 100 ms) conditions. By using the known nauseogenic frequency of 0.2 Hz and a less nauseogenic frequency of 1.0 Hz, one can determine whether the varying amplitude of latency is actually the causal mechanism for increased sickness or if it is the varying amplitude of latency paired with the known nauseogenic 0.2 Hz frequency that causes increased sickness.

The frequency determined to be sensitive for humans, 0.2 Hz, was chosen as the nauseogenic stimulus due to the amount of previous research that provides evidence for the claim that humans are highly susceptible to sickness when the frequency is around 0.2 Hz (O'Hanlon & McCauley, 1974; Donohew & Griffin, 2009; Donohew & Griffin, 2004; Golding, Phil, & Markey, 1996; Golding, et al., 2001; Godling, et al., 2007; Bijveld, et al., 2008;Godling, et al., 2009; St. Pierre, 2012; Diels & Howarth, 2013). The less nauseogenic frequency of 1.0 Hz was chosen due to the known significant sickness drop off after 0.5 Hz that has been shown to continue decreasing to 1.0 Hz (O'Hanlon & McCauley, 1974; Golding, et al., 1997; Diels & Howarth, 2013).

Hypotheses. The first hypothesis was a main effect of frequency, i.e., that there will be an increased level of simulator sickness and motion sickness experienced in the 0.2 Hz frequency of latency condition than in the 1.0 Hz frequency of latency condition. This hypothesis is supported by the numerous experiments previously conducted that determined humans are highly susceptible to sickness around 0.2 Hz frequency (O'Hanlon & McCauley, 1974; Donohew & Griffin, 2009; Donohew & Griffin, 2004; Golding, Phil, & Markey, 1996; Golding, et al., 2001; Godling, et al., 2007; Bijveld, et al., 2008;Godling, et al., 2009; St. Pierre, 2012; Diels & Howarth, 2013).

The second hypothesis was a main effect of amplitude, i.e., that there will be an increased level of simulator sickness and motion sickness experienced in the varying amplitude of sinusoidal latency condition than in the fixed amplitude of sinusoidal latency condition. This result has been shown in St. Pierre's study with both conditions having f = 0.2 Hz (St. Pierre, 2012). However, it has not been looked at using a known less nauseogenic frequency of 1.0 Hz.

The third hypothesis was that there would be a significant interaction between frequency of latency and amplitude of latency. If the evidence supports this hypothesis, it would replicate the results found by St. Pierre (2012).

METHODS

Participants

A power analysis was conducted using "PS: Power and Sample Size" and used frequency of latency data collected from St. Pierre's 2012 study. The current study used

a continuous response variable from independent control and experimental subjects with one control per experimental subject. In a previous study the response within each subject group was normally distributed with standard deviation 38.67 (St. Pierre, 2012). If the true difference in motion sickness between the experimental and control means is 30.05, as found by St. Pierre (2012), 27 experimental subjects (f = 0.2 Hz) and 27 control subjects (f = 1.0 Hz) needed to be studied to be able to reject the null hypothesis with the population means of the experimental and control groups are equal with probability (power) 0.8. The Type 1 error probability associated with this test of the null hypothesis was set to 0.05. The sample size was increased initially to 30 subjects per each experimental condition (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms), (A = 20 – 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms) and 30 subjects per each control condition (A = 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms), (A = 20 – 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms) to account for the unknown magnitude of effect of amplitude of latency. However, since the interaction between frequency and amplitude of latency is of interest, the study was over-powered, with 60 subjects in the experimental conditions and 60 in the control conditions to make sure there was enough power to see the interaction if there is one.

One hundred twenty participants were recruited from Clemson University's student population. Participants were recruited via the Clemson Psychology Research System subject pool recruitment system and word of mouth. Those responding from the subject pool were compensated $10 for their time and were given course credit through

the Clemson Psychology Research System; those responding from word of mouth were compensated $10 for their time.

All recruited participants completed a screening questionnaire to determine if they were eligible for participation. Individuals who self-reported high susceptibility and frequency of MS symptoms were excluded from the experiment. Additionally, individuals who had past experience with virtual environments or HMDs were excluded from the experiment. Individuals who self-reported any history of brain, heart, stomach, eye (other than corrected vision), or inner ear problems, or who were pregnant were not eligible for this experiment. If the individual had corrected vision, they were required to wear contact lenses to participate, as the HMD could not fit over glasses. Finally, participants who reported feeling sick or less than their normal physical state were rescheduled and sent home for the day. Participants were asked to abstain from alcohol, nicotine, and caffeine for 12 hours prior to their appointment. They were also asked to avoid intense physical activity the hour before their appointment.

Design

This experiment had a 2 x 2 between subjects design (see figure 5). A between subjects design was chosen to avoid adaptation effects between conditions among subjects and to reduce potential participant withdrawal between each condition.

		Frequency	
		1 Hz	.2 Hz
Amplitude	100 ms fixed	N = 30	N = 30
	20 – 100 ms varying	N = 30	N = 30

Table 2.1: 2 x 2 between subjects design

The dependent variable was incidence of simulator sickness. The two independent variables were frequency of latency and amplitude of latency, each with two levels. The amplitude of latency levels (A = 100 ms and A = 20 – 100 ms) were used by St. Pierre, and were found to have a significant effect on simulator sickness (2012). The frequency of latency levels were f = 0.2 Hz and f = 1.0 Hz. The 0.2 Hz condition was chosen because 0.2 Hz has been found to be the most sickening frequency for humans in other areas. According to previous motion sickness research, humans are highly susceptible to sickness around 0.2 Hz frequency (O'Hanlon & McCauley, 1974; Donohew & Griffin, 2009; Donohew & Griffin, 2004; Golding, Phil, & Markey, 1996; Golding, et al., 2001; Godling, et al., 2007; Bijveld, et al., 2008;Godling, et al., 2009; St. Pierre, 2012; Diels & Howarth, 2013). Previous research also found a quick decrease in nausea at 0.5 Hz, and this drop off is known to continue to 1.0 Hz (Golding, et al., 1997). This is why 1.0 Hz. was chosen as the second condition. Participants were randomly assigned to one of the four conditions.

Materials and Apparatus

HMD. A *ProView TM XL 50* HMD (Kaiser Electro-Optics, Inc.) was used for this experiment, shown in figure 6. The *XL 50* is a bi-ocular HMD with a resolution of 1024 x 768 and a frame rate of 60 Hz. Eyecups made out of rubber-like molding made specifically for the *XL 50* were used to occlude external light from the environment. This is necessary because the camera is mounted on top of the HMD and there was a discrepancy in height between the environment and the HMD display.

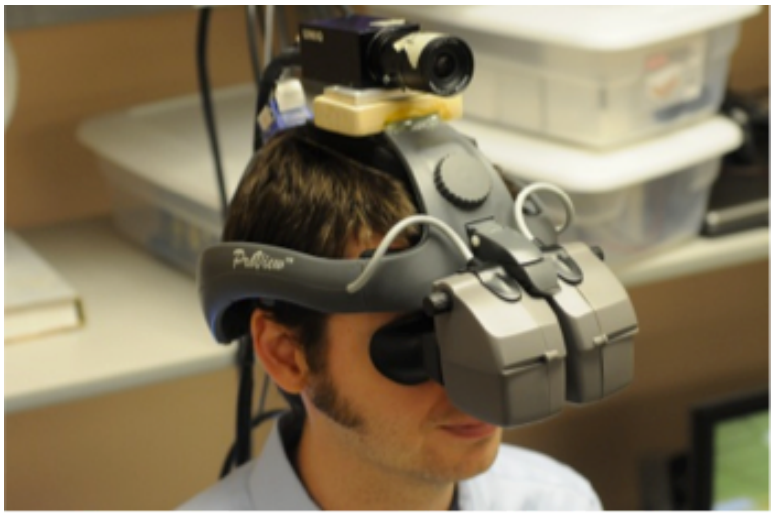


Figure 2.1: Picture of HMD that will be used in this experiment

The HMD had a 50° field of view (FOV) diagonally, 30° FOV vertically, and 40° FOV horizontally. It weighed 35 oz prior to camera being mounted.

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. The camera resolution was 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.

A Dalsa *X64 CL Express*™ PCI camera link frame grabber for image capture was installed on a Windows XP computer containing 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 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; cited from St. Pierre, 2012).

> 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.

Ryan Mattfeld, a graduate student in the Electrical and Computer Engineering department at Clemson University modified the update delay program to be able to create the specific latencies used in this experiment: (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms), (A = 20 – 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms), (A = 100 ms, f = 1.0 Hz,

K = 100 ms, B = 70 ms), (A = 20 – 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms), and assisted with the validation of this program.

Validating the update delay program. To confirm the fidelity of the update delay program the amplitude of latency and frequency of latency were measured to confirm the program operated accurately. The outside observer method was used to ensure the program was measuring the correct frequency and amplitude of latency. The procedure involved using a camera as a sensor and the HMD display as an actuator. A black bar was moved across a white background and a high-speed camera was used to capture both the sensed and actuated images. The latency was measured between the sensed and the actuated images of the black bar moving across the white background.

When measuring the latency using this method it is difficult to see multiple cycles of latency, especially when f = 0.2 Hz. When frequency is 0.2 Hz, it takes 5 seconds to complete one cycle. However, each recording using the outside observer method is a maximum of 2 seconds, resulting in only around 1/5 of a latency cycle. This makes it impossible to see the varying amplitude component of the latency. Because of this, 10 recordings of each condition using the outside observer method were made and a range of frequency and amplitude values were looked at using sinusoidal fits to ensure the update delay program was doing what was expected. This data can be seen in Appendix A. Sinusoidal fits were applied to the raw data using the following equation:

$$y = A*\sin[(1/f)x + \Phi] + k$$

where ‘A’ represents amplitude of latency, ‘f’ represents frequency of latency, ‘Φ’ represents phase shift and ‘k’ represents constant offset. Values were found first using

this equation with no fixed variables, and then by fixing k to 180, and A and f to the appropriate values for the condition being tested. Figure 7 shows what the latency would look like over a 20 second period for each condition.

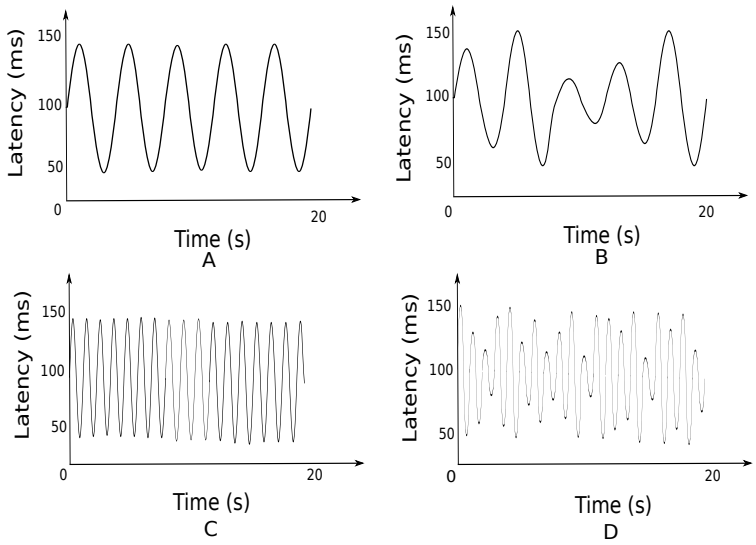


Figure 2.2: simulated latency over a 20 second time period for each condition. The x-axis depicts time in seconds and the y-axis depicts latency in milliseconds. Graph A represents latency with (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); graph B represents latency with (A = 20 – 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); graph C represents latency with (A = 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms); graph D represents latency with (A = 20 – 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms).

Results from the outside observer method show that the software was able to produce the four conditions in the HMD display, shown in figure 8. Figure 8 shows a graph of the frequency and amplitude of latency from each condition. Figure 8A shows results from latency with (A = 20 – 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); figure 8B shows results from latency with (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); figure 8C shows results from latency with (A = 20 – 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms); figure 8D shows results from latency with (A = 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms). Each of these figures represents the change in system latency over

time. Appendix B shows more examples of latency graphs from the outside observer method. Figure 9 shows graphs of the alignment of event properties between the sensed and actuated images from before motion starts to after it stops. The areas of the graph that overlap represent both images being in the same position. The discrepancy between the lines represents the latency in the system.

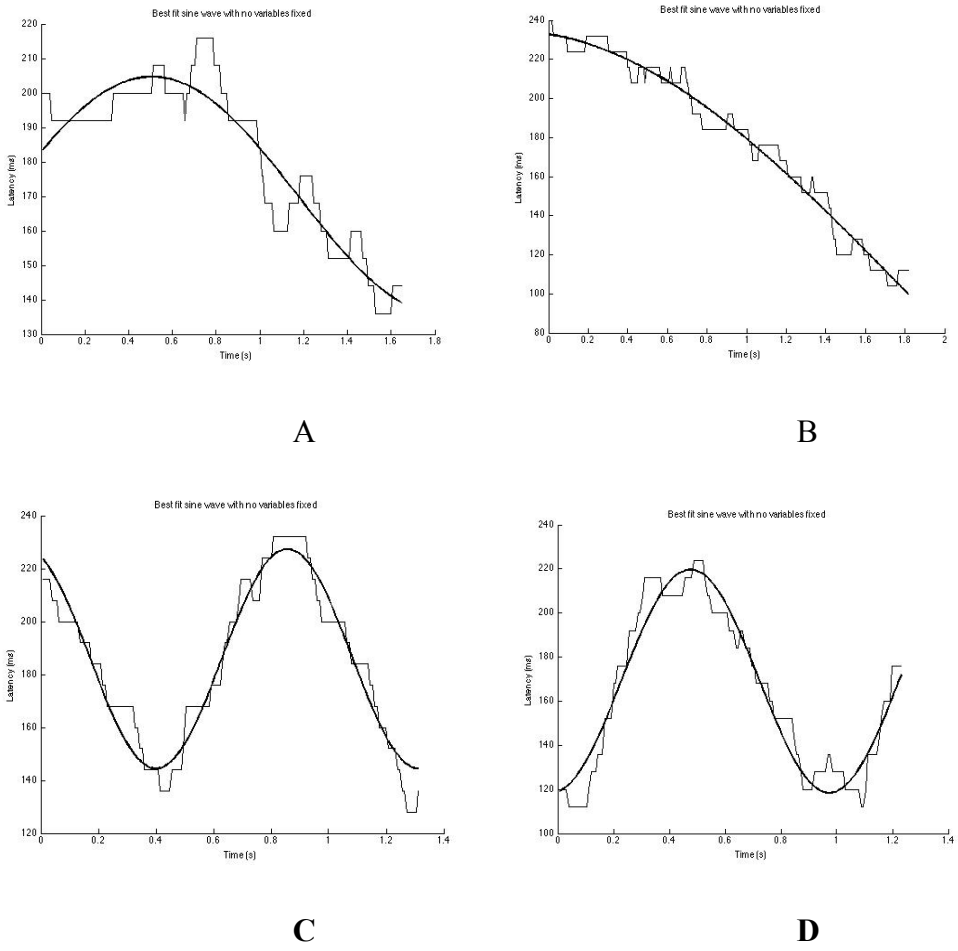


Figure 2.3: Graphs displaying results from the outside observer method. The x-axis depicts time in milliseconds and the y-axis shows latency in milliseconds. Graph A latency with (A = 20 – 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); graph B represents latency with (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); graph C represents latency with (A = 20 – 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms); graph D represents latency with (A = 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms).

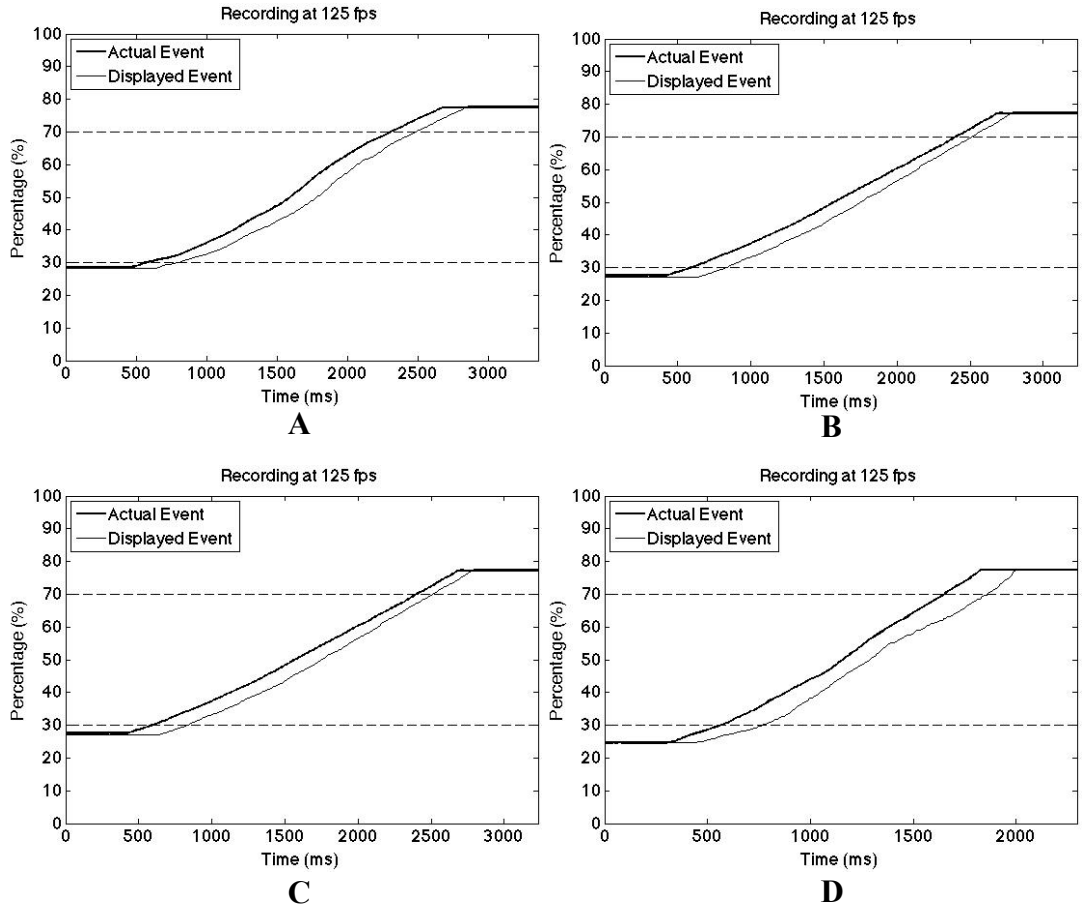


Figure 2.4: Graphs showing alignment between sensed and actual image. Graph A latency with (A = 20 – 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); graph B represents latency with (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); graph C represents latency with (A = 20 – 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms); graph D represents latency with (A = 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms).

Motion Sickness History Questionnaire. The Motion Sickness History Questionnaire (MSHQ) is a diagnostic tool used to assess susceptibility to motion sickness based on participants' self-report of relevant sickening experiences and was used to measure previous experience with motion sickness (Reason & Brand, 1975). It also assesses how frequently participants were involved in certain modes of traveling (plane, boat, train, etc.) and how frequently those modes of travel initiated motion sickness

symptoms. The MSHQ results in one total score, and the higher the score, the more susceptible to motion sickness the individual is.

Simulator Sickness Questionnaire. The Simulator Sickness Questionnaire (SSQ) is a measure of motion sickness symptoms in a virtual environment, called simulator sickness (Kennedy et al., 1993). This questionnaire requires participants to respond to how they are feeling regarding 16 different sickness symptoms on a scale of none, slight, moderate, or severe, with corresponding raw scores of 0, 1, 2, 3. There are three subscales of this questionnaire: oculomotor, disorientation, and nausea. Each participant yielded a Total Severity (TS) score for each subscale by summing the individual items under each subscale. The maximum score is 224.4. The creators of the questionnaire stated SSQ scores between 5-10 indicate minimal symptoms, 10-15 indicate significant symptoms, and scores above 20 indicate a bad virtual environment simulator.

Motion Sickness Assessment Questionnaire. The Motion Sickness Assessment Questionnaire (MSAQ) is a multidimensional measure assessing motion sickness (Gianaros et al., 2001). There are 16 items on this questionnaire, and participants responded to how they are feeling based on each of the items. Participants responded using a 9-point scale (1 = not at all, 9 = severe) for each item and the maximum score is 144.

Room Layout. An object location task was used to challenge the participants' visual-vestibular interaction. Participants were required to locate 8 objects around the laboratory throughout the experiment. They did this by making head movements while

wearing the HMD. The layout of the room is shown in Figure 10. The objects, shown in figure 11, were the office door (A), clock (B), flag (C), fire extinguisher (D), front door (E), first aid kit (F), fan (G), and curtain (H). Participants' performance on the object location task was judged based on whether the object being located was in the visual display before the next object needed to be located.

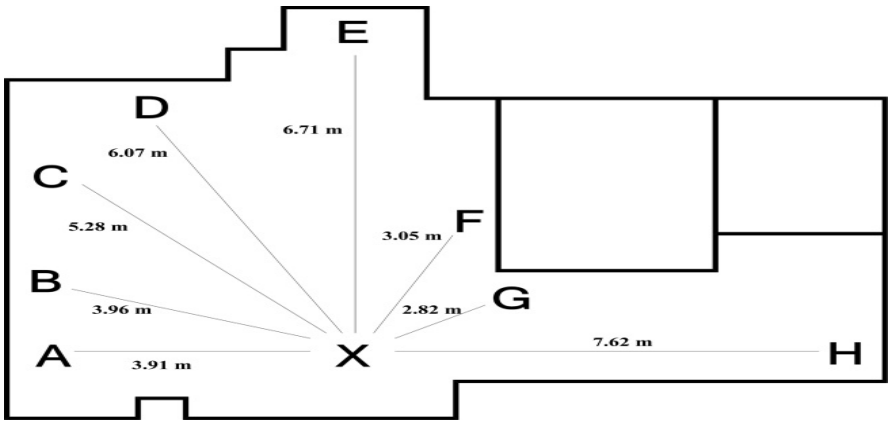


Figure 2.5: Footprint of room layout for the object location task

Figure 2.6: Picture of objects that were found in the object location task during trials.

Procedure

Upon arrival, each participant received a copy of the Clemson University Internal Review Board approved informed consent form to read and sign. Participants were then

screened for a history of brain, heart, vision, stomach, or inner ear problems. Participants were also screened for pregnancy, vertigo, and past experience with virtual environments and/or HMDs. Any participants answering yes to the previous screening questions were not permitted to participate in the experiment. Participants were then given the MSHQ to assess their motion sickness history and susceptibility to motion sickness.

Remaining participants were then escorted to the laboratory where the experiment took place. The experimenter explained the object location task and asked if the participant had any questions regarding this task. The participant was asked to stand in a specific spot for the object location task and to hang on to a handrail placed in front of them for the duration of the experiment. They were informed to not lock their knees during the experiment, as this can decrease blood flow to the brain. Next, the participant was guided through equipping the HMD. The experimenter helped participants put on the HMD when necessary. When the participant indicated the HMD was adjusted appropriately, the experimenter started the experiment. The experimenter then verbally administered a pre-practice MSAQ and SSQ.

The HMD task required participants to make head movements while wearing the HMD. Participants were asked to find objects around the lab based on their names and locations. A voice recording was used to call out the name of the object and its relative direction compared to where the previous object was located (e.g. left or right). The object order was randomized. The maximum horizontal movement indicated by stimulus arrangement was 180°. Participants were instructed to make movements with only their head and neck. If necessary, slight shoulder movements were allowed, but participants

were instructed to not make hip or leg movements during the task. Participants were instructed to center the objects within the HMD display. In between trials, participants were asked to look straight ahead at an 'X' placed on the front door.

Each participant completed two 48-second practice trials. The practice trials were necessary for the participant to become familiar with the objects and their locations, as well as to get a feel for the speed of the object location task. After both practice trials, the experimenter again verbally administered the MSAQ and the SSQ.

The experiment entailed five two-minute experimental trials with a one-minute break between trials. There were 40 head movements in each trial separated by three seconds. During each trial, the experimenter recorded the accuracy of the head movements via a monitor displaying the projected images in the HMD display. At the end of each trial during the one-minute break, the experimenter verbally administered the SSQ. After the final trial, the experimenter immediately verbally administered the MSAQ and the SSQ while the participant was still wearing the HMD.

Participants were instructed that the goal of this experiment was not to make them feel too uncomfortable and if at any time they started to feel to uncomfortable they should let the experimenter know and the study would be stopped immediately. In between each trial, the experimenter asked the participant if they felt fit enough to continue with the experiment. If the participant felt too uncomfortable to continue with the experiment, the experimenter instructed them to cease the object location task and close their eyes. The experimenter quickly removed the HMD from the participant's head and helped them to a chair situated adjacent to where the participant was standing.

The experimenter then asked the participant if they needed any water and made sure the participant stayed seated until they felt better.

After completing five experimental trials, the participant was asked to take off the HMD. The experimenter debriefed the participant on the purpose of the study and again verbally administered the SSQ to make sure the participant was well enough to leave the lab. Before the participants left, the experimenter compensated them with $10.

Data Analysis

Peak SSQ scores were used to measure simulator sickness among participants and post experimental MSAQ scores were used to measure motion sickness among participants. Each participant had eight total SSQ scores (completed before practice trials, after practice trials, after trial 1, 2, 3, 4, and 5, and after experimental debrief) and three total MSAQ scores (completed before practice trials, after practice trials, and after experimental trials) upon completion of the experiment. The peak scores for SSQ were used instead of the sum or the mean for two reasons: to be able to use participants who withdrew from the experiment before completing all five trials, and to account for varying onset and severity of simulator sickness across individuals.

A 2 x 2 between subjects analysis of variance (ANOVA) was run to determine if there were significant differences in simulator sickness symptoms between the four conditions. A second 2 x 2 between subjects ANOVA was run to look for significant differences in motion sickness symptoms in each condition. The dependent variables being analyzed for each test were the peak SSQ score and post experimental MSAQ score for each participant, respectively. The independent variables were frequency of latency

and amplitude of latency for both ANOVAs. Both independent variables had two levels (0.2 Hz and 1.0 Hz in the frequency of latency condition, and 100 ms fixed amplitude and 20-100 ms varying amplitude in the amplitude of sinusoidal latency condition).

Another 2x2 ANOVA was run using post SSQ scores as the dependent variable, and keeping frequency and amplitude of latency as the independent variables. This analysis was run to make sure there were no significant changes between the peak and post SSQ scores.

A mixed ANOVA was run to look for an effect of trial by condition. This analysis used only participants who completed all five experimental trials. The peak SSQ scores were used for the dependent variable. The between subjects independent variable was assigned condition and the within subjects independent variable was trial.

To analyze participant withdrawal, a Fisher's exact test was used. This test compared the number of participants who did not complete all five experimental trials to the number of participants who did. The independent variables for this analysis were again frequency (0.2 Hz vs. 1 Hz) and amplitude (100 ms fixed vs. 20 – 100 ms varying) of sinusoidal latency.

RESULTS

One hundred twenty four participants were recruited for this experiment (60 male). Initially, 120 participants were recruited. However, four participants in the 1 Hz frequency 100 ms amplitude condition had peak SSQ scores greater than 3 standard deviations from the mean. In each of these cases, factors not related to the experimental

procedure may have contributed to their sickness, such as race and high susceptibility to motion sickness. One participant dropped out of the study after locating only three objects in the object location task and had severe symptoms (loss of vision and hearing for a few seconds); one participant exhibited unusually high SSQ scores during the practice trials; one participant dropped out after the third experimental trial with unusually high SSQ scores; one participant was African American/Asian and had a high MSHQ score (cf. the high MS genetic susceptibility in Asian populations; Stern et al., 1996). Therefore, it was decided to replace them with additional participants. Of the remaining 120 participants, there were 30 participants in each condition (14 males in condition 1, 15 males in conditions 2, 3, and 4).

The mean age for all 120 participants was 19.4 years (*SD* = 1.51). The mean age for males was 19.7 years (*SD* = 1.79), and the mean age for females was 19.1 years (*SD* = 1.14). Of the 120 participants, 25 did not complete all five experimental trials. All of these participants reported feeling too uncomfortable to continue with the experiment due to common SS symptoms such as dizziness, eyestrain, and nausea. Of the 25 participants who stopped the HMD exposure early, two started to collapse right before stopping the experiment and complained of being extremely lightheaded after the experiment, and two vomited a few minutes after stopping the experiment.

Table 1 shows the number of participants whose peak SSQ scores occurred in each of the five experimental trials. The frequency distributions for both peak SSQ scores and MSAQ scores were positively skewed (see figures 12 and 13). However,

distributions for each condition had a similar shape so it was determined the data could be analyzed with analyses of variance (ANOVA) without transformation.

Trial Number	1	2	3	4	5
# participants with Peak SSQ occuring in this trial	8	5	7	5	95

Table 3.1: Number of participants experiencing peak SSQ scores in each experimental trial

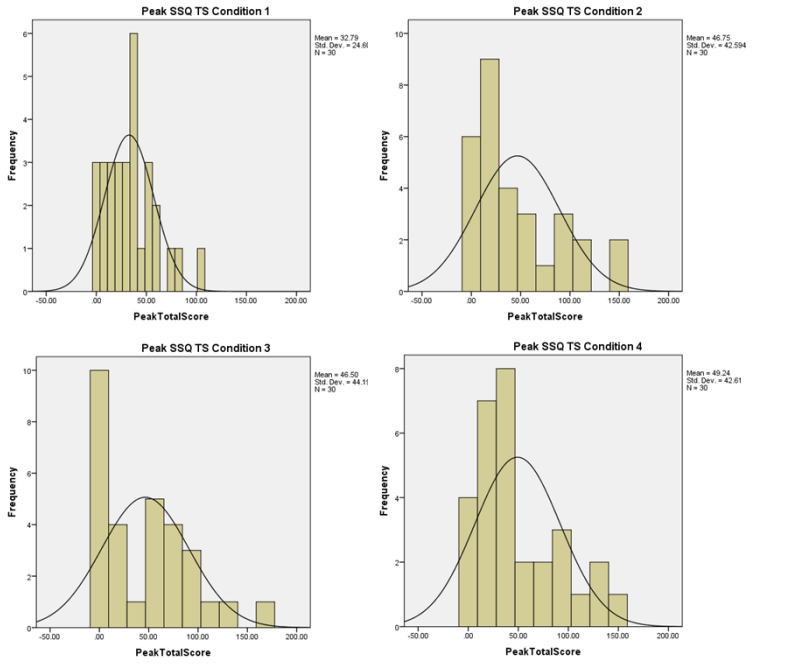


Figure 3.1: Frequency distribution of peak SSQ scores for all conditions

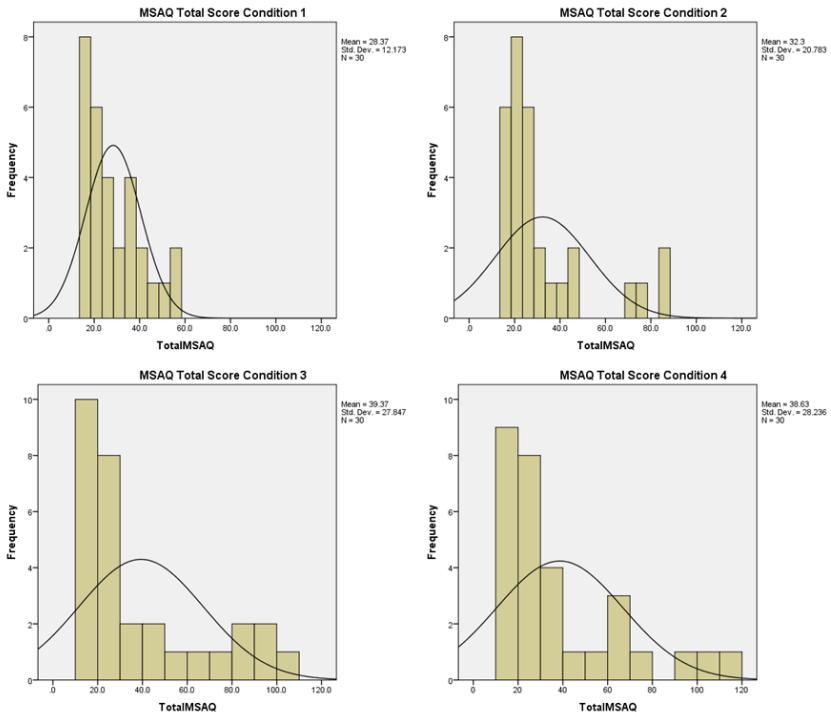


Figure 3.2: Frequency distribution of total MSAQ scores for all conditions

Tests of the Hypotheses

SSQ Results. To test if there were increased simulator sickness symptoms in the .2 Hz frequency condition compared to the 1.0 Hz frequency condition as well is if there were increased simulator sickness symptoms in the 20 – 100 ms varying amplitude conditions compared to the 100 ms fixed amplitude conditions a 2 (frequency) x 2 (amplitude) ANOVA was conducted. Peak SSQ scores were used during analysis to measure simulator sickness so participants who stopped HMD exposure early could still be included in the analysis. Means and standard deviations for each condition were calculated using peak SSQ scores for each participant (see Table 2). No significant main effect of frequency, $F(1, 116) = 1.27$, $p = 0.26$, $\eta^2 = .011$, or main effect of amplitude,

$F(1, 116) = 1.35$, $p = 0.25$, $\eta^2 = .012$, was found. There was also no significant interaction, $F(1, 116) = 0.61$, $p = 0.44$, $\eta^2 = .005$.

		Frequency		
		1 Hz	.2 Hz	
Amplitude	100 ms fixed	32.8 ± 24.6	46.5 ± 44.2	39.6 ± 36.1
	20 – 100 ms varying	46.8 ± 42.6	49.2 ± 42.6	48.0 ± 42.3
		39.8 ± 35.2	47.9 ± 43.1	

Table 3.2: Table of peak SSQ total scores means, standard deviations, and sample sizes for each condition

MSAQ Results. To test if there were increased motion sickness symptoms in .2 Hz frequency condition compared to the 1.0 Hz frequency condition as well is if there were increased motion sickness symptoms in the 20 – 100 ms varying amplitude conditions compared to the 100 ms fixed amplitude conditions a 2 (frequency) x 2 (amplitude) ANOVA was conducted. MSAQ total scores were used to measure levels of motion sickness experienced by participants. Means and standard deviations were calculated for each condition from total MSAQ scores from each participant (see table 3). A significant main effect of frequency of latency was found, $F(1, 116) = 4.19$, $p = .043$, $\eta^2 = .035$. No significant main effect of amplitude of latency occurred, $F(1, 116) = 0.14$, $p = .71$, $\eta^2 = .001$. No significant interaction between frequency and amplitude of latency was found, $F(1, 116) = 0.30$, $p = 0.58$, $\eta^2 = .003$.

		Frequency		
		1 Hz	.2 Hz	
Amplitude	100 ms fixed	28.3 ± 12.2	39.3 ± 27.9	33.9 ± 22.0
	20 – 100 ms varying	32.3 ± 20.8	38.6 ± 28.2	35.5 ± 24.8
		30.3 ± 17.0	39.0 ± 27.8	

Table 3.3: Table of MSAQ total scores means, standard deviations and sample sizes for each condition

Effect of trial. A mixed ANOVA was conducted to look at the effect of trial by condition. The analysis was completed on only the 95 participants who completed all five HMD trials. Figure 14 shows a graph of average SSQ total scores across the five trials for each condition. A significant main effect of trial was found, F (1, 91) = 64.66, p < .01, η^2 = .42. No significant main effect of condition was found, F (1, 91) = .532, p = .66, η^2 = .017. No significant interaction was found between trial and condition, F(1, 91) = .24, p = .87, η^2 = .008.

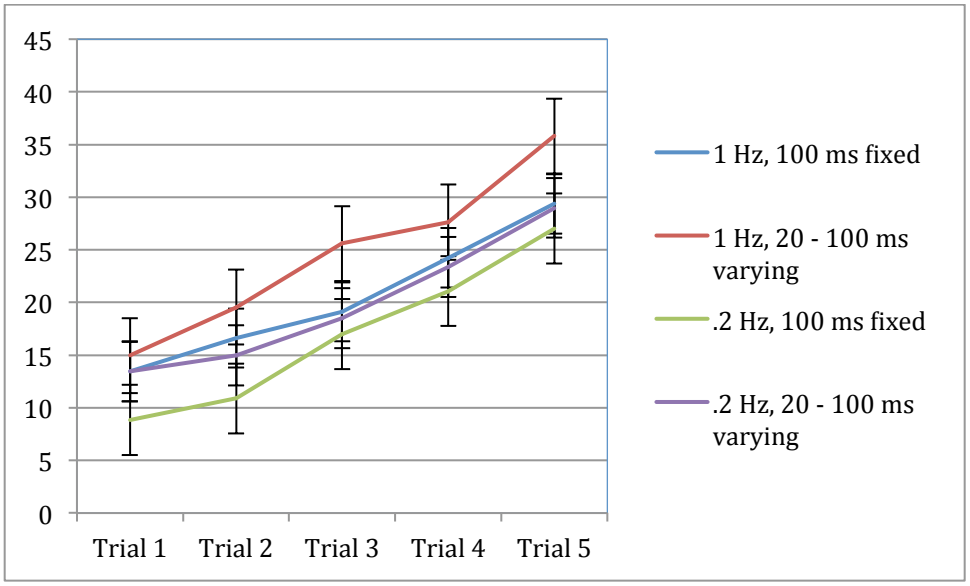


Figure 3.3: Line graph of average SSQ total score across experimental trials for each condition.

Early Termination Analysis. Twenty-five participants were not able to complete the five experimental trials and terminated HMD exposure. Table 4 shows the number of participants that dropped out by condition. Expected cell counts were low (near 5), so the assumptions for a chi square test were violated. Therefore, a Fisher's

exact test was run to examine effects of frequency and amplitude on early termination. Data were collapsed across the two amplitude conditions to look for an effect of frequency. No significant effect of frequency was found, $p = .33$. Data were also collapsed across the two frequency conditions to look for an effect of amplitude. A significant effect of amplitude was found, $p = .011$.

		Frequency		
		1 Hz	.2 Hz	
Amplitude	100 ms fixed	3/30	4/30	7/60
	20 – 100 ms varying	8/30	10/30	18/60
		11/60	14/60	

Table 3.4: Number of participants who did not complete the five experimental trials by condition

Exploratory Data Analysis

Post Trial SSQ. Post trial SSQ scores were analyzed in addition to peak SSQ. Means and standard deviations for each of the conditions are shown in table 5. No significant main effect of frequency, $F(1, 116) = 1.42$, $p = .26$, $\eta^2 = .012$, or amplitude, $F(1, 116) = 1.51$, $p = .22$, $\eta^2 = .013$ was observed and no significant interaction was observed, $F(1, 116) = .53$, p .47, $\eta^2 = .005$.

		Frequency		
		1 Hz	.2 Hz	
Amplitude	100 ms fixed	30.4 ± 25.2	44.4 ± 43.8	37.4 ± 36.1
	20 – 100 ms varying	44.6 ± 43.2	48.0 ± 43.7	43.3 ± 43.1
		37.5 ± 35.8	46.2 ± 43.4	

Table 3.5: Post Trial SSQ score means and standard deviations by condition

Further examination of Amplitude of Latency. To further examine the amplitude of latency variable, a 2x2 ANOVA was conducted using .2 Hz frequency conditions from the current experiment and the .2 Hz frequency conditions from a previous experiment. Means and standard deviations for each of these conditions are shown in table 6. There was a marginally significant main effect of amplitude found, $F(1, 116) = 3.84$, $p = .052$, $\eta^2 = .032$. There was no significant effect of experimenter, $F(1,116) = .001$, $p = .98$, $\eta^2 = .00$. Finally, there was no significant interaction between amplitude of latency and experimenter, $F(1, 116) = 2.53$, $p = .12$, $\eta^2 = .021$.

		Condition		
		.2 Hz, 100 ms fixed	.2 Hz, 20 – 100 ms varying	
Experimenter	Matt	34.5 ± 33.5	60.8 ± 41.2	47.7 ± 39.5
	Amelia	46.5 ± 44.2	49.2 ± 42.6	47.9 ± 43.1
		40.5 ± 39.4	55.0 ± 42.0	

Table 3.6: Peak SSQ means and standard deviations for .2 Hz frequency conditions in previous and current study

DISCUSSION

Primary Purpose

The primary purpose of this study was to examine the effect of frequency (f = 0.2 Hz and f = 1.0 Hz) and amplitude (A = 100 ms and A = 20 – 100 ms) on varying latency on simulator sickness and motion sickness in a head mounted display. It was predicted that an increased level of simulator and motion sickness symptoms would occur in the 0.2 Hz frequency conditions and the 20 – 100 ms varying amplitude conditions. It was also predicted that there would be a significant effect of trial, meaning sickness symptoms would increase as exposure time to stimulus increased.

Frequency and Amplitude and Their Relationship to Motion Sickness

Discussion of simulator sickness and motion sickness results. Analysis of peak SSQ scores and post-trial MSAQ scores yielded similar results, with one notable exception. It was hypothesized that simulator sickness and motion sickness would increase during 0.2 Hz frequency conditions and 20 – 100 ms varying amplitude conditions. This hypothesis was not supported using results from peak SSQ scores, and was only partially supported using post MSAQ scores. A significant effect of frequency of latency was found using MSAQ post trials scores, indicating that on average, participants in 0.2 Hz conditions had higher symptoms of motion sickness. This finding was not significant when using peak SSQ scores, however the data trended in the same direction. The mean peak SSQ scores in both the varying amplitude conditions were higher than the mean peak scores in the fixed amplitude conditions. Additionally, the mean peak SSQ score for both .2 Hz frequency conditions was higher than the 1 Hz frequency fixed amplitude condition and were relatively the same as the 1 Hz frequency varying amplitude condition. These findings coincide with previous research indicating humans are sensitive to motion around 0.2 Hz frequency (O'Hanlon & McCauley, 1974; Donohew & Griffin, 2009; Donohew & Griffin, 2004; Golding, Phil, & Markey, 1996; Golding, et al., 2001; Godling, et al., 2007; Bijveld, et al., 2008;Godling, et al., 2009; St. Pierre, 2012; Diels & Howarth, 2013) and varying amplitude of latency being more sickening than fixed amplitude of latency (St. Pierre, 2012).

SSQ post trials. There was a discrepancy between significant results from peak SSQ scores and MSAQ post trials scores (MSAQ scores resulted in a significant main effect of frequency of latency, while peak SSQ trended in the same direction but were not significant). Because of this, SSQ post trial scores were analyzed. Again, there were no significant effects of frequency or amplitude of latency or an interaction using SSQ post trial scores. However, when looking at the means for all conditions, both the varying amplitude conditions were higher than the mean peak scores in the fixed amplitude conditions. Additionally, the mean peak SSQ score for both .2 Hz frequency conditions was higher than the 1 Hz frequency fixed amplitude condition and were relatively the same as the 1 Hz frequency varying amplitude condition. The trend in these data follow previous research indicating humans are highly susceptible to sickness when frequency is around 0.2 Hz (O'Hanlon & McCauley, 1974; Donohew & Griffin, 2009; Donohew & Griffin, 2004; Golding, Phil, & Markey, 1996; Golding, et al., 2001; Godling, et al., 2007; Bijveld, et al., 2008;Godling, et al., 2009; St. Pierre, 2012; Diels & Howarth, 2013) and varying amplitude of latency as more sickening than fixed amplitude of sinusoidal latency (St. Pierre, 2012). Interestingly, these results also show that varying amplitude increases simulator sickness when paired with a non-sickening frequency as compared to fixed amplitude paired with the same non-sickening frequency. While an effect of frequency may be more dominant, varying amplitude of latency, especially when paired with non-sickening frequencies still seems to have an important effect on sickness symptoms.

Varying Amplitude of Latency and Participant Withdrawal. The current study found a significant relationship between participant withdrawal and condition. A total of 25 participants did not complete all five experimental trials. This equates to 20.8% of all participants. When determining whether frequency and/or amplitude of latency significantly contributed to participant withdrawal, a significant effect of amplitude was found on early termination rate. These results indicate that significantly more participants had to terminate their participation before the end of the experiment in the varying amplitude conditions than in the fixed amplitude conditions. There was not a significant difference in early termination rate between the .2 Hz conditions and the 1 Hz conditions. This finding further supports previous research suggesting that there is in fact an effect of varying amplitude of latency on simulator sickness (St. Pierre, 2012). While significant effects of frequency were found via survey data collected from this experiment, the significant effect of amplitude on early termination rate argues that amplitude, as well as frequency, is an important contributing factor to simulator sickness in HMDs. The effect of amplitude on early termination rate raises the point that varying amplitude may lead to more severe sickness symptoms than the effect of frequency of latency on sickness when there is incidence of sickness in the participant, leading the participant to stop the experiment early. This idea should be further examined in future experiments and will be discussed more extensively in the "Future Work" section.

Previous Studies and the Current Experiment. To further examine the effect of amplitude of latency on simulator sickness, results from the current study were compared to results from St. Pierre's 2012 study. Both studies had the 0.2 Hz, 100 ms fixed

amplitude and the 0.2 Hz, 20-100 ms varying amplitude conditions. When looking at only these two conditions in both experiments, a marginally significant effect of amplitude of latency was found. This result shows that participants in the varying amplitude conditions demonstrated significantly higher sickness symptoms than those in the fixed amplitude conditions. This finding suggests that amplitude of latency does indeed play a role in simulator sickness along with frequency of latency, and that varying amplitude of latency results in significantly greater sickness symptoms than fixed amplitude of sinusoidal latency.

Effect of Trial. The hypothesis predicting there would be increased sickness symptoms with increased duration of exposure to stimulus was supported. Analyzing effect of trial revealed a significant main effect of trial during this study, meaning sickness symptoms increased as trials increased. Participants reported increased sickness symptoms the longer they were in the experiment. This increase was consistent across all four experimental conditions; there was no difference in increase depending on experimental condition. This analysis only included participants who completed all five experimental trials so the effect of time while exposed to the stimulus could be accurately examined. No significant effect of condition was found in terms of effect of trial, indicating that regardless of the condition each participant was in, sickness symptoms systematically increased over time. This finding aligns with previous research concluding that longer exposure time leads to increased sickness levels (Moss, 2008; St. Pierre, 2012).

Virtual Environments and Head Mounted Displays

Designers of HMDs and virtual environments are faced with a tradeoff between enhancing optical realism and decreasing system latency (Moss, 2008). Hettinger and Riccio found evidence that pictoral realism contributes to system latency (1992). Many studies found evidence to support the idea that system latency has the potential to cause simulator sickness (DiZio & Lackner, 1997; Jennings, et al., 2004). Recent findings specify that this system latency is varying, and not constant, which could be a contributing factor in simulator sickness as well (Wu, Dong, & Hoover, 2013). Findings from the current study, in addition to findings from St. Pierre, support this notion that variable latency increases simulator sickness and that both frequency and amplitude of latency are important factors in simulator sickness (2012). If system latency has to be compromised when designing virtual environments and HMDs, then designers should make sure amplitude of latency is not varying and frequency of latency is not around 0.2 Hz. While latency will still be prevalent and perhaps noticeable by humans, following these guidelines should reduce sickness among users.

Motion Sickness and Simulator Sickness

Findings from this experiment contribute to the existing knowledge of simulator sickness. The results from this experiment as well as past experiments from the Applied Human Psychophysiology Laboratory at Clemson University show that variable latency is a key factor in experiencing simulator sickness in HMDs. More specifically, from the current and previous experiments it is known that humans are highly susceptible to sickness when frequency of latency is around 0.2 Hz or when amplitude of latency is varying between 20 – 100 ms. Having a better understanding of simulator sickness can

help prevent sickness symptoms in the future. This experiment aids in identifying specific relationships between frequency and amplitude of latency and simulator sickness in HMDs and contributes to research dedicated to helping people adapt to and/or overcome added latency in HMDs. Results from this experiment can also contribute to designing HMDs for future use to reduce simulator sickness in users by potentially reducing variable latency, making sure frequency of latency is not in the 0.2 Hz range, and keeping amplitude of latency from varying. Virtual environments and HMDs are used to advance fields such as medicine, engineering, design, training, and entertainment. Virtual environments can be used for training when on the job training is too risky. If users are experiencing motion sickness or simulator sickness from this training, it may lead to poor job performance, loss of equipment, or loss of health to the user. Continuing this line of research will positively impact many jobs that require employees to interact with virtual environments or HMDs on a daily basis, such as teleoperations and other military personnel, laparoscopic surgeons, and astronauts.

Limitations

There are a few limitations to this study that should be noted. First, the study was a between-subjects design, and therefore individual differences play a role in the results. While participants were screened to minimize individual differences in motion sickness susceptibility, it is recommended that a within-subjects design be used in future studies. Also, all participants were between the ages of 18 and 27 years, and were primarily Caucasian, resulting in a narrow sample size regarding age and race, both of which can be factors in motion sickness susceptibility (Golding, 2006). There was an even number

of male and female participants in the current experiment, but there was always a female experimenter administering the study, which could have affected the results of the surveys differently for male and female participants.

Another limitation to the current experiment is potential reporting bias from participants. All data analyzed for the current study were survey responses, and the experimenter administered all surveys verbally. This procedure could have caused some participants to not be truthful in their responses to the surveys, or to not acknowledge their symptoms completely to the experimenter.

A possible confound in this paradigm is that participants were required to remain standing for the duration of the experiment. While participants were frequently reminded to not lock there knees, it is possible that some participants did lock their knees, causing them to feel light headed or some other symptom of simulator sickness.

There is a possible limitation in the surveys used to collect sickness symptom data, as the MSAQ yielded a significant main effect of frequency of latency and the SSQ did not. There are many possible explanations for this finding, for example, the two questionnaires are measuring two different syndromes: motion sickness and simulator sickness. While these syndromes are similar, there are some differences in experienced symptoms (Bijveld, et al., 2008). This discrepancy could also be due to the two questionnaires having different dimensionalities (using a 1 – 9 scale vs. None, Slight, Moderate, Severe scale), incorporating different items, or being administered at different times during the experiment (just pre and post trials vs. between all experimental trials).

Finally, the current experiment only looked at two frequencies of latency (f = 0.2 Hz and f = 1.0 Hz) out of the continuum of possible frequencies. This limits the generalizability of the results found, because only few frequencies relative to all possible frequencies have been tested in this paradigm. Additionally, only two types of amplitudes of latency were tested (A = 100 ms and A = 20 – 100 ms), again limiting the generalizability of the results.

Future Work

In the future, a within-subjects design should be used to avoid individual differences and reduce error variance in the data. Survey data should be collected without verbal administration. One way this could be done is project the survey in the HMD between experimental trials so participants can read and complete the surveys by themselves, without the help of the experimenter. Additionally, physiological data should be coupled with survey data to avoid reporting bias from participants.

Future studies should further examine the role of amplitude of latency on both incidence and severity of simulator sickness. There are numerous previous studies looking at the effects of frequency, specifically 0.2 Hz frequency, on sickness, and there is overwhelming evidence that 0.2 Hz frequency causes humans to be extremely susceptible to sickness (O'Hanlon & McCauley, 1974; Donohew & Griffin, 2009; Donohew & Griffin, 2004; Golding, Phil, & Markey, 1996; Golding, et al., 2001; Godling, et al., 2007; Bijveld, et al., 2008;Godling, et al., 2009; St. Pierre, 2012; Diels & Howarth, 2013). However, there is a gap in the literature when it comes to varying amplitude of latency and simulator sickness (St. Pierre, 2012).

Experimenters should continue to look at varying amplitude of latency, specifically in known non-sickening frequencies. Both fixed and varying amplitude should be tested, using fixed amplitude as a control group. Frequencies between 0.2 Hz and 1.0 Hz should be incrementally coupled with fixed and varying amplitude to fully examine the relationship between sickening and non-sickening frequencies and varying amplitude. The current study found a significant effect of amplitude of latency on early termination rate of participants. This finding may indicate that upon incidence of sickness, varying amplitude results in more severe symptoms than 0.2 Hz frequency. This idea needs to be further explored in future studies by noting early termination rate of participants. This idea can also be looked at using physiological data in addition to survey data to determine the severity of symptoms when participants are experiencing simulator sickness. Future work in this area has the potential to solidify the notion that varying amplitude contributes to simulator sickness, and will give insight on the extent to which varying amplitude matters in system latency.

Conclusion

In conclusion, results from this study support previous findings showing an effect of frequency on simulator sickness, specifically 0.2 Hz frequency causing an increase in sickness symptoms. Results from this study provide evidence that amplitude of latency plays a role in simulator sickness as well, but the specific role of amplitude of latency needs to be further explored in future studies. Findings from this experiment contribute to the overwhelming evidence that humans are sensitive to 0.2 Hz frequency found in previous studies (O'Hanlon & McCauley, 1974; Donohew & Griffin, 2009; Donohew &

Griffin, 2004; Golding, Phil, & Markey, 1996; Golding, et al., 2001; Godling, et al., 2007; Bijveld, et al., 2008;Godling, et al., 2009; St. Pierre, 2012; Diels & Howarth, 2013). Results from this study show a trend toward a significant main effect of amplitude of latency, which has not been explored extensively prior to this experiment. In 2008 the Applied Human Psychophysiology Laboratory began to examine the cause of sickness when wearing an HMD. Moss (2008) found marginal support for his hypothesis that update delay contributed to sickness. Then Wu, Dong, and Hoover (2013) found *variable latency* in HMDs. Results from St. Pierre (2012) and the present study supports the notion that this variable latency is contributing to the problem of simulator sickness in HMDs.

APPENDICES

Appendix A

1 Hz Frequency, 100 ms fixed Amplitude

	No fixed variables			
Recording	K	A	F	Phi
81	162.91	86.09	1.07	0.96
82	168.98	101.31	1.00	-1.44
87	181.06	105.23	0.83	0.96
88	168.38	110.21	0.72	2.18
89	164.85	83.29	1.19	-0.78
90	157.59	79.20	0.98	-0.77
91	166.16	108.33	0.89	0.13
92	187.85	101.87	1.07	0.54
93	183.36	84.19	0.90	-0.76
94	190.89	90.26	1.06	0.16
Average	173.20	95.00	0.97	0.12
Standard Deviation	11.56	11.57	0.14	1.09

	K fixed to 180			
Recording	K	A	F	Phi
81	180.00	101.10	0.77	2.06
82	180.00	105.77	1.03	-1.57
87	180.00	105.01	0.84	0.92
88	180.00	28.96	4.77	0.14
89	180.00	107.49	0.93	-0.29
90	180.00	121.62	0.72	-0.16
91	180.00	86.63	1.10	-0.19
92	180.00	103.98	1.06	0.54
93	180.00	85.38	0.91	-0.76
94	180.00	94.68	1.04	0.22
Average	180.00	94.06	1.32	0.09
Standard Deviation	0.00	25.20	1.22	0.98

	K fixed to 180 AND A fixed to 100			
Recording	K	A	F	Phi
81	180.00	100.00	0.77	2.06
82	180.00	100.00	1.03	-1.58
87	180.00	100.00	0.83	0.92
88	180.00	100.00	0.71	2.44
89	180.00	100.00	0.93	2.87
90	180.00	100.00	0.65	3.11
91	180.00	100.00	1.09	-0.21
92	180.00	100.00	1.06	0.54
93	180.00	100.00	0.90	-0.73
94	180.00	100.00	1.04	0.21
Average	180.00	100.00	0.90	0.96
Standard Deviation	0.00	0.00	0.16	1.60

	K fixed to 180 AND F fixed to 1.0			
Recording	K	A	F	Phi
81	180.00	82.15	1.00	1.21
82	180.00	105.56	1.00	-1.47
87	180.00	105.24	1.00	0.30
88	180.00	116.40	1.00	1.93
89	180.00	107.13	1.00	-0.45
90	180.00	129.76	1.00	-0.54
91	180.00	85.62	1.00	0.03
92	180.00	103.54	1.00	0.85
93	180.00	82.00	1.00	-1.10
94	180.00	94.00	1.00	0.42
Average	180.00	101.14	1.00	0.12
Standard Deviation	0.00	15.45	0.00	1.05

0.2 Hz Frequency, 100 ms fixed Amplitude

	No fixed variables			
Recording	K	A	F	Phi
95	105.49	258.10	0.13	1.74
96	-1524.70	3534.20	0.05	1.38
97	-2812.40	6115.50	0.04	1.41
98	146.96	21.40	1.10	-2.83
99	195.42	45.61	0.41	-1.53
100	1057.70	1971.60	0.02	1.09
101	-855.71	2158.20	0.03	-1.39
102	164.00	203.18	0.20	1.03
Average	-440.40	1788.47	0.25	0.11
Standard Deviation	1232.39	2169.80	0.37	1.75

	K fixed to 180			
Recording	K	A	F	Phi
95	180	205.86	0.12	2.43
96	180	126.70	0.27	0.50
97	180	132.64	0.26	0.37
98	180	733.40	0.01	3.26
99	180	71.63	0.27	-0.48
100	180	214.84	0.09	-0.03
101	180	38.85	1.14	4.08
102	180	172.23	0.22	0.95
Average	180	212.02	0.30	1.39
Standard Deviation	0	219.33	0.35	1.66

	K fixed to 180 AND A fixed to 100			
Recording	K	A	F	Phi
95	180	100	0.30	1.35
96	180	100	0.23	0.72
97	180	100	0.21	0.64
98	180	100	0.09	-0.99
99	180	100	0.30	-0.58
100	180	100	0.20	0.06
101	180	100	0.22	2.42
102	180	100	0.21	0.95
Average	180	100	0.22	0.57
Standard Deviation	0	0	0.06	1.08

	K fixed to 180 AND F fixed to .2			
Recording	K	A	F	Phi
95	180	138.07	0.20	1.98
96	180	116.08	0.20	0.96
97	180	120.29	0.20	0.73
98	180	78.56	0.20	10.92
99	180	66.28	0.20	-0.20
100	180	127.02	0.20	-0.17
101	180	118.01	0.20	-0.68
102	180	173.04	0.20	1.13
Average	180	117.17	0.20	1.83
Standard Deviation	0	33.27	0.00	3.77

1.0 Hz Frequency, 20 – 100 ms varying Amplitude

	No fixed variables			
Recording	K	A	F	Phi
105	172.17	70.61	0.91	-1.00
106	176.73	57.94	1.02	-0.66
107	169.59	22.38	2.47	2.06
108	178.52	59.92	1.25	-1.63
109	185.84	82.89	1.10	10.61
110	187.75	54.50	1.08	-0.14
111	190.13	81.58	0.95	2.53
112	190.75	47.14	0.94	1.69
113	180.77	54.31	1.07	0.90
114	179.93	47.40	1.09	0.36
115	197.52	78.54	1.03	0.32
116	180.17	15.12	1.11	-1.13
Average	182.49	56.03	1.17	1.16
Standard Deviation	8.13	21.48	0.42	3.25

	K fixed to 180			
Recording	K	A	F	Phi
105	180	64.33	1.07	-1.47
106	180	60.66	0.94	-0.48
107	180	43.14	1.22	8.96
108	180	58.44	1.29	-1.76
109	180	81.90	1.10	10.68
110	180	60.25	1.06	-0.07
111	180	20.04	2.31	-4.24
112	180	42.93	0.97	1.32
113	180	54.24	1.07	0.89
114	180	47.36	1.09	0.36
115	180	81.21	1.01	0.32
116	180	15.21	1.10	-1.10
Average	180	52.48	1.19	1.12
Standard Deviation	0	20.55	0.37	4.33

	K fixed to 180 AND A fixed to 60			
Recording	K	A	F	Phi
105	180	60	1.08	-1.49
106	180	60	0.94	2.66
107	180	60	1.23	-2.73
108	180	60	1.29	-1.75
109	180	60	1.12	1.80
110	180	60	1.06	-0.07
111	180	60	0.97	2.32
112	180	60	0.97	1.36
113	180	60	1.07	0.89
114	180	60	1.10	0.33
115	180	60	1.01	0.36
116	180	60	1.10	-1.02
Average	180	60	1.08	0.22
Standard Deviation	0	0	0.10	1.70

	K fixed to 180 AND F fixed to 1.0			
Recording	K	A	F	Phi
105	180	65.71	1.00	-1.27
106	180	59.60	1.00	-0.63
107	180	40.45	1.00	32.66
108	180	54.60	1.00	-1.12
109	180	82.14	1.00	-0.83
110	180	57.79	1.00	0.15
111	180	74.57	1.00	-1.02
112	180	42.75	1.00	1.16
113	180	53.28	1.00	1.22
114	180	44.80	1.00	0.72
115	180	81.12	1.00	0.38
116	180	14.86	1.00	-0.87
Average	180	55.97	1.00	2.55
Standard Deviation	0	19.10	0.00	9.53

0.2 Hz Frequency, 20 – 100 ms varying Amplitude

	No fixed variables			
Recording	K	A	F	Phi
117	927.64	1657.40	0.02	2.09
118	753.63	1948.90	0.02	-1.40
119	4251.10	8947.30	0.01	1.54
120	2505.10	5470.40	0.03	1.46
121	170.13	69.06	0.37	-5.91
122	96.90	531.83	0.00	2.76
Average	1450.75	3104.15	0.08	0.09
Standard Deviation	1623.95	3435.05	0.15	3.26

	K fixed to 180			
Recording	K	A	F	Phi
117	180	147.62	0.11	5.94
118	180	2186.30	0.01	3.11
119	180	85.45	0.17	1.15
120	180	103.14	0.22	0.63
121	180	57.47	0.48	0.02
122	180	393.01	0.01	3.06
Average	180	495.50	0.16	2.32
Standard Deviation	0	837.17	0.18	2.18

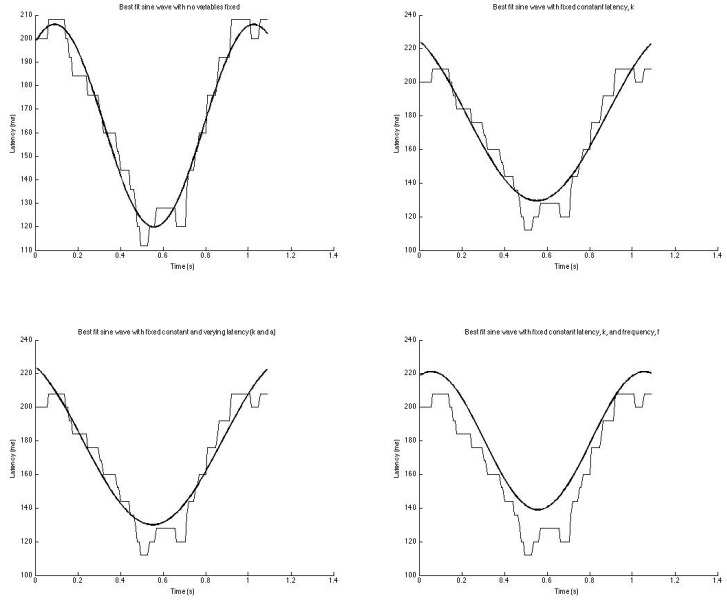
	K fixed to 180 AND A fixed to 60			
Recording	K	A	F	Phi
117	180	60	0.24	2.39
118	180	60	0.20	2.02
119	180	60	0.13	1.18
120	180	60	0.18	0.89
121	180	60	0.48	0.01
122	180	60	0.30	0.20
Average	180	60	0.25	1.12
Standard Deviation	0	0	0.12	0.96

	K fixed to 180 AND F fixed to .2			
Recording	K	A	F	Phi
117	180	93.54	0.2	-19.49
118	180	61.04	0.2	-13.71
119	180	86.66	0.2	0.87
120	180	100.88	0.2	0.81
121	180	68.12	0.2	1.96
122	180	25.70	0.2	0.94
Average	180	72.66	0.2	-4.77
Standard Deviation	0	27.53	3.04047E-17	9.35

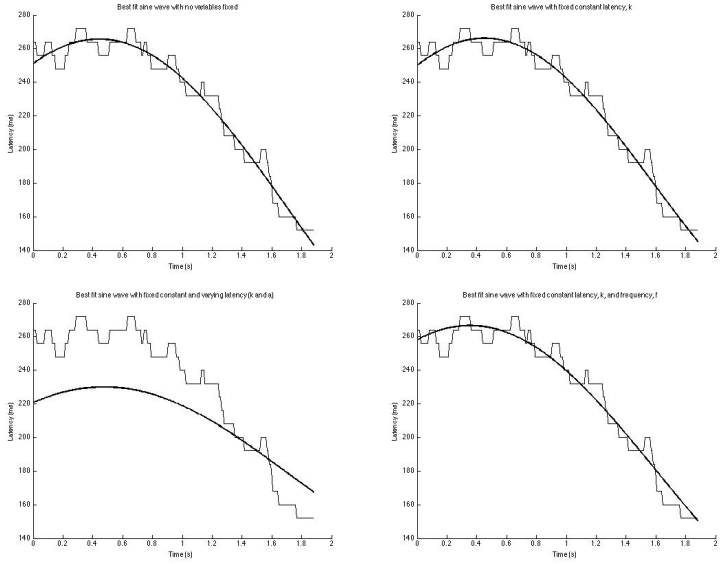
Appendix B

Examples of the four graphs showing system latency with fitted sine waves for each condition are shown below. The graph in the top left corner shows the sine wave fitted with no variables fixed. The graph in the top right corner shows the sine wave fitted with constant offset (k) fixed to 180. The graph in the bottom left corner shows the sine wave fitted with constant off set and amplitude (A) fixed. The graph in the bottom right corner shows the sine wave fitted with constant off sent and frequency (f) fixed.

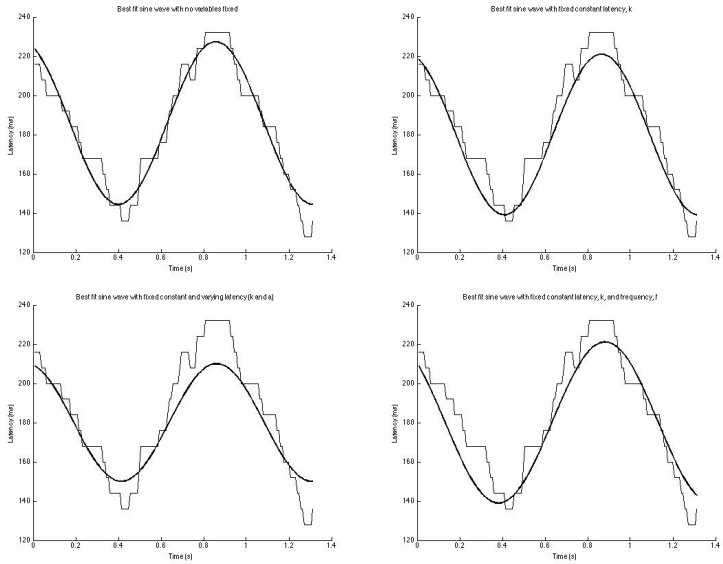
1.0 Hz Frequency, 100 ms Amplitude, 100 ms Constant Offset



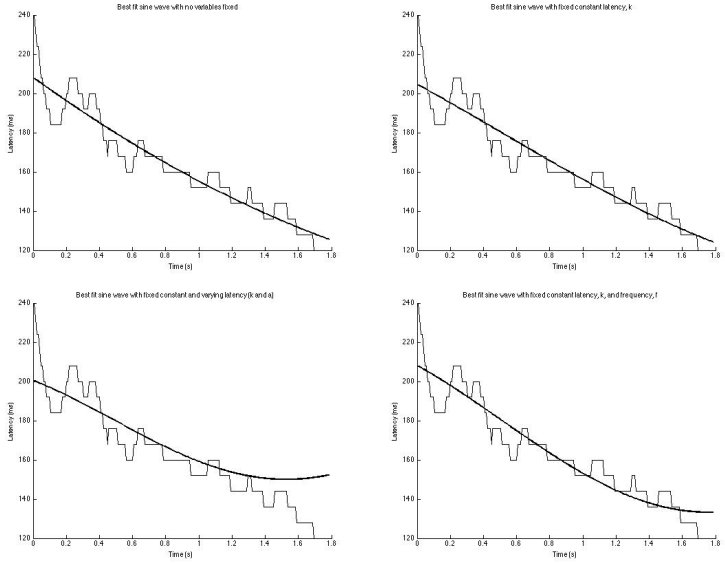
0.2 Hz Frequency, 100 ms fixed Amplitude, 100 ms constant offset



1.0 Hz Frequency, 20 – 100 ms varying Amplitude, 100 ms constant offset



.2 Hz Frequency, 20 – 100 ms varying Amplitude, 100 ms constant offset



REFERENCES

Alexander, S., Cotzin, M., Klee, J., & Wendt, G. (1947). Studies of motion sickness: XVI. the effects upon sickness rates of waves of various frequencies but identical acceleration. *Journal of Experimental Psychology, 37*(5), 440.

Ash, A., Palmisano, S., Govan, D. G., & Kim, J. (2011). Display lag and gain effects on vection experienced by active observers. *Aviation, Space, and Environmental Medicine, 82*(8), 763-769.

Bijveld, M., Bronstein, A. M., Golding, J. F., & Gresty, M. A. (2008). Nauseogenicity of off-vertical axis rotation vs. equivalent visual motion. *Aviation, Space, and Environmental Medicine, 79*(7), 661-665.

Diels, C., & Howarth, P. A. (2013). Frequency characteristics of visually induced motion sickness. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 55*(3), 595-604.

DiZio, P., & Lackner, J. R. (1997). Circumventing side effects of immersive virtual environments. Paper presented at the *Hci (2),* 893-896.

Donohew, B. E., & Griffin, M. J. (2004). Motion sickness: Effect of the frequency of lateral oscillation. *Aviation, Space, and Environmental Medicine, 75*(8), 649-656.

Draper, M. H., Viirre, E. S., Furness, T. A., & Gawron, V. J. (2001). Effects of image scale and system time delay on simulator sickness within head-coupled virtual environments. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 43*(1), 129-146.

Duh, H. B., Parker, D. E., Philips, J. O., & Furness, T. A. (2004). "Conflicting" motion cues to the visual and vestibular self-motion systems around 0.06 hz evoke simulator sickness. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 46*(1), 142-153.

England, R. (1995). *Simulated and virtual realities: Elements of perception* CRC Press.

Gianaros, P. J., Muth, E. R., Mordkoff, J. T., Levine, M. E., & Stern, R. M. (2001). A questionnaire for the assessment of the multiple dimensions of motion sickness. *Aviation, Space, and Environmental Medicine, 72*(2), 115.

Golding, J. F. (2006). Motion sickness susceptibility. *Autonomic Neuroscience*, *129*(1), 67-76.

Golding, J., Arun, S., Wortley, E., Wotton-Hamrioui, K., Cousins, S., & Gresty, M. (2009). Off-vertical axis rotation of the visual field and nauseogenicity. *Aviation, Space, and Environmental Medicine, 80*(6), 516 – 521.

Golding, J., Finch, M., & Stott, J. (1997). Frequency effect of 0.35-1.0 hz horizontal translational oscillation on motion sickness and the somatogravic illusion. *Aviation, Space, and Environmental Medicine, 68*(5), 396-402.

Golding, J., & Markey, H. (1996). Effect of frequency of horizontal linear oscillation on motion sickness and somatogravic illusion. *Aviation, Space, and Environmental Medicine, 67*(2), 121-126.

Golding, J. F., Mueller, A., & Gresty, M. A. (2001). A motion sickness maximum around the 0.2 hz frequency range of horizontal translational oscillation. *Aviation, Space, and Environmental Medicine, 72*(3), 188-192.

Hettinger, L. J., & Riccio, G. E. (1992). Visually induced motion sickness in virtual environments. *Presence: Teleoperators and Virtual Environments, 1*(3), 306-310.

Howarth, P., & Costello, P. (1997). The occurrence of virtual simulation sickness symptoms when an HMD was used as a personal viewing system. *Displays, 18*(2), 107-116.

Kennedy, R. S., Drexler, J. M., Compton, D. E., Stanney, K. M., Lanham, S., & Harm, D. L. (2001). Configural scoring of simulator sickness, cybersickness and space adaptation syndrome: Similarities and differences?

Kennedy, R. S., Drexler, J., & Kennedy, R. C. (2010). Research in visually induced motion sickness. *Applied Ergonomics, 41*(4), 494-503.

Kennedy, R. S., Hettinger, L. J., & Lilienthal, M. G. (1990). Simulator sickness. *Motion and space sickness*, 317-341.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology, 3*(3), 203-220.

Lawther, A., & Griffin, M. J. (1987). Prediction of the incidence of motion sickness from the magnitude, frequency, and duration of vertical oscillation. *The Journal of the Acoustical Society of America, 82*, 957.

Lippi, V., Avizzano, C. A., Mottet, D., & Ruffaldi, E. (2010). Effect of delay on dynamic targets tracking performance and behavior in virtual environment. Paper presented at the *Ro-Man, 2010 IEEE,* 446-451.

Money, K. (1972). Measurement of susceptibility to motion sickness. *AGARD CP—109.Technical Editing and Reproduction, Ltd., London,*

Morice, A. H., Siegler, I. A., & Bardy, B. G. (2008). Action-perception patterns in virtual ball bouncing: Combating system latency and tracking functional validity. *Journal of Neuroscience Methods, 169*(1), 255-266.

Moss, J. D., Austin, J., Salley, J., Coats, J., Williams, K., & Muth, E. R. (2011). The effects of display delay on simulator sickness. *Displays, 32*(4), 159-168.

Moss, J. D., & Muth, E. R. (2011). Characteristics of head-mounted displays and their effects on simulator sickness. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 53*(3), 308-319.

Moss, J. D., Muth, E. R., Tyrrell, R. A., & Stephens, B. R. (2010). Perceptual thresholds for display lag in a real visual environment are not affected by field of view or psychophysical technique. *Displays, 31*(3), 143-149.

Moss, J., Scisco, J., & Muth, E. (2008). Simulator sickness during head mounted display (HMD) of real world video captured scenes. Paper presented at the *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 52*(19), 1631-1634.

O'Hanlon, J. F., & McCauley, M. E. (1973). *Motion Sickness Incidence as a Function of the Frequency and Acceleration of Vertical Sinusoidal Motion,*

Oman, C. M. (1990). Motion sickness: A synthesis and evaluation of the sensory conflict theory. *Canadian Journal of Physiology and Pharmacology, 68*(2), 294-303.

Pausch, R., & Crea, T. (1992). A literature survey for virtual environments: Military FlightSimulator visual systems and simulator sickness.

Reason, J. T., & Brand, J. J. (1975). *Motion sickness.* London: Academic Press.

Riccio, G. E., & Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology, 3*(3), 195-240.

Sadowski, W., & Stanney, K. (2002). Presence in virtual environments.

Singer, M., & Witmer, B. (1996). Presence measures for virtual environments: Background and development. *Draft United States Army Research Institute for the Behavioral and Social Sciences,*

Smart, L. J., Stoffregen, T. A., & Bardy, B. G. (2002). Visually induced motion sickness predicted by postural instability. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 44*(3), 451-465.

Stanney, K. M., Mourant, R. R., & Kennedy, R. S. (1998). Human factors issues in virtual environments: A review of the literature. *Presence: Teleoperators and Virtual Environments, 7*(4), 327-351.

Stoffregen, T. A., Draper, M. H., Kennedy, R. S., & Compton, D. (2002). Vestibular adaptation and aftereffects. *Handbook of Virtual Environments: Design, Implementation, and Applications,* , 773-790.

Stoffregen, T. A., & Smart Jr, L. J. (1998). Postural instability precedes motion sickness. *Brain Research Bulletin, 47*(5), 437-448.

Teather, R. J., Pavlovych, A., Stuerzlinger, W., & MacKenzie, I. S. (2009). Effects of tracking technology, latency, and spatial jitter on object movement. Paper

presented at the *3D User Interfaces, 2009. 3DUI 2009. IEEE Symposium on,* 43-50.

Toet, A., Jansen, S. E., & Delleman, N. J. (2007). Effects of field-of-view restrictions on speed and accuracy of manoeuvring 1, 2, 3. *Perceptual and Motor Skills, 105*(3f), 1245-1256.

van Emmerik, M. L., de Vries, S. C., & Bos, J. E. (2011). Internal and external fields of view affect cybersickness. *Displays, 32*(4), 169-174.

Witmer, B., & Singer, M. (1994). Measuring immersion in virtual environments. *US Army Res.Inst., Alexandria, VA, Tech.Rep, 1014*

Wu, W., Dong, Y., & Hoover, A. (2013). Measuring digital system latency from sensing to actuation at continuous 1-ms resolution. *Presence: Teleoperators and Virtual Environments, 22*(1), 20-35.