The Effect of Varying Latency in a Head-Mounted Display on Task Performance and Motion Sickness

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THE EFFECT OF VARYING LATENCY IN A HEAD-MOUNTED DISPLAY ON TASK PERFORMANCE AND MOTION SICKNESS

A Dissertation
Presented to
the Graduate School of
Clemson University

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

by
Michael Lee Wilson
August 2016

Accepted by:
Dr. Eric R. Muth, Committee Chair
Dr. Adam W. Hoover
Dr. Benton D. Lawson
Dr. Christopher C. Pagano
Abstract

The purpose of this study was to determine how latency in a head-mounted display affects human performance. Virtual environments are used frequently for training, however simulator sickness is a common problem and may affect transfer of training. Aspects of virtual environments that cause simulator sickness are not fully understood, but varying latency has been shown to increase simulator sickness symptoms. The impact of varying latency on task performance and the interaction between performance and simulator sickness symptoms has not been examined. Twenty-nine subjects (15 male) participated in a repeated measures study in which they were exposed to two different latency conditions in a Head-Mounted Display (HMD): constant (70 ms) and varying (70 ms – 270 ms). Experimental sessions were separated by 14-days to minimize the effects of adaptation. While wearing the HMD, subjects used a laser pointer to repeatedly "shoot" at 8 laser targets, arrayed in a 180-degree arc around the lab, over the course of 200 trials per session, presented in 5 blocks of 40 trials. Sickness levels, accuracy and time-to-hit data were recorded for analysis. Subjects scored fewer hits and took longer to hit targets in the varying latency condition, $F(1,54) = 35.20$, $p < .01$, $\eta_p^2 = .40$, than in the constant latency condition $F(4,51) = 13.50$, $p < .01$, $\eta_p^2 = .51$. These findings indicate that individuals exposed to varying latency performed worse than individuals exposed to constant latency. However, it is unclear if the performance effects are due mostly to the latency itself or another underlying causal influence such as simulator sickness.
Dedication

I would like to dedicate this dissertation to my wife Susan. Your love, devotion and untiring support have not only made this journey possible, but also made it a fun adventure. You had to leave behind your home, your job and your friends in order to support my dream and that speaks volumes to just how special you truly are. You are still my best friend, my strongest supporter and harshest critic. You had the foresight to realize that I needed to change my life in order to be truly happy. Fortunately, you pushed me to pursue those dreams to make it happen. I can honestly say that I am now headed in a new direction with a renewed sense of self and purpose and I owe it to you. I can't wait to see where this change will take us as we begin the next chapter of our lives. Thank you for helping me "live the dream". I love you!
Acknowledgements

I would like to express my sincere thanks to all of the people who helped me complete this project. First, I would like to thank my advisor Dr. Eric Muth. Thank you for not only taking a chance on me, but also for not giving up. Your passion for teaching, coaching and mentoring are an inspiration for all to emulate. You have helped me grow more than you will ever know and I appreciate it.

Next, I would also like to thank my Committee Members Dr. Adam Hoover, Dr. Ben Lawson and Dr. Chris Pagano for dedicating their time and efforts to this project, I really appreciate the support, insight, criticisms and suggestions. A special thank you to Ryan Mattfeld for the programming work on the automation tool used in this research. Thank you to my lab mates, Phil Jasper, Amelia Kinsella and James Salley and Dr. Bjoern Horing, for their feedback and support throughout the project. I also need to thank the Creative Inquiry undergraduates, Jessica Bonsack, Jackie McSorley and Mimi Land for their help with pilot testing and data collection.

Lastly, I would like to thank the Clemson University Human Factors Institute for the grant that funded the supplies and subject payments for this study and the Science, Mathematics & Research for Transformation Scholarship program for the financial support for the past three years while completing this degree.
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CHAPTER I

Introduction

Purpose

The purpose of this study was to determine how latency in a head-mounted display affects human performance. Latency is defined as the time it takes for a real-world event to be sensed, processed, and displayed (Wu, Dong, & Hoover, 2013). Time delays due to latency can distort our visual perception of our environment. Perceptual distortions such as those caused by prisms have been investigated for centuries (Eagleman, 2001). However, new technologies such as wearable visual monitors create different perceptual distortions requiring similar detailed study. Our laboratory has found that head-tracking error leads to varying latency in visual displays (Wu et al., 2013), that is, as a head-mounted display (HMD) wearer is moving their head, the visual images being displayed are delayed in varying amounts. We have also observed that an increase in the variability of latency is related to increased sickness levels for HMD users (Moss et al., 2011). However, we have yet to examine if this increased variability in latency affects task performance in an HMD.

An Historical Perspective on Visual Perception

The study of how visual perception occurs and how it can influence our environment is not easy. Visual perception depends on information transmitted through complex neural networks and cognitive processing based on memories and past experiences. Perceptual distortions are possible at any point during this process, and are in fact, quite common. Strange sensations such as trying a new glasses prescription,
quickly standing up, a minor ear infection and consuming alcohol are some examples of these perceptual distortions that we routinely experience. Similar perceptual distortions are caused by technologies that manipulate our visual environment such as an HMD or a 3D television set. These technologies create distortions to visual perception through various means, e.g. time delays, 2D viewing of a 3D image or optical transmission. Some visual distortions even cause adverse visual-vestibular interactions. Since vision is important to how the majority of people interact with the world, visual perception continues to be an area of interest for research (Wade & Swanston, 2013). An example of this is the detailed body of work on how prisms cause perceptual rearrangement and how humans have adapted to these rearrangements. This line of research is summarized in the comprehensive review by Robert Welch, who suggests that "human beings are capable of modifying their behavior in response to almost every imaginable stable rearrangement of vision" (Welch, 1978, p.276). Perceptual distortions caused by new technologies are analogous to those caused by prisms, but have the potential to introduce novel perceptual rearrangements. Therefore, these new technologies require the same level of investigative rigor that has been applied to the perturbations caused by prismatic rearrangement.

**Technology and Visual Perception**

Modern technologies, e.g., night vision goggles, expand human capabilities. In the case of night vision goggles, allowing individuals to view the world outside when ambient light levels are below human visual perceptual thresholds. These technologies also have the potential to introduce new challenges to how we perceive and interact with our environment. In the example of night vision devices, they provide a 2-dimensional
image of the world, lacking normal cues used to judge depth perception and estimate distance. To counter these differences in visual perception, night vision device users are taught techniques, such as scanning, to help them interpret images. Similarly, other 2-dimensional depictions of the world, such as video display terminals, create challenges when they are used to remotely view inaccessible locations or to manipulate remote objects, e.g., oil well valves at extreme sea depths. Workers using video displays, often report symptoms such as eyestrain, headache and blurred vision that may be induced by the perceptual challenges (Thomson, 1998). These problems are often exacerbated when using wearable monitors such as an HMD (Patterson, Winterbottom, & Pierce, 2006).

**The Head Mounted Display (HMD)**

HMDs are worn on the head and close to the eyes providing users with an image resulting in a virtual visual surround. Technology allows for the motion of the head to be tracked and the display to be updated to correspond with head movements (Held & Durlach, 1989). These displays are sometimes referred to as head-tracked HMDs. Although commonly used for entertainment, they are increasingly being used by workers performing remote operations, maintenance, engineering, and simulations (Garcia Sanchez et al., 2015; Peli, 1998). Users of HMDs routinely encounter perceptual modifications such as delays in movement feedback or occlusion of peripheral vision that interfere with perception. As many as 80% of HMD users experience nausea, dizziness, sweating, vertigo, or other symptoms similar to the symptoms of motion sickness (Davis, Nesbitt, & Nalivaiko, 2014). Additional research is needed to understand how these devices cause sickness and affect performance in order to limit or reduce their effects.
Motion Sickness

Motion sickness refers to a maladaptation syndrome associated with exposure to real and/or apparent motion (Lawson, 2014). The cardinal signs or symptoms are nausea (possibly leading to retching/vomiting), increased salivation, pallor, cold sweating, and drowsiness (Lawson, 2014; Wood, Kennedy, & Graybiel, 1966). There are a variety of competing theories of motion sickness including the sensory conflict theory (Reason & Brand, 1975a), Riccio and Stofferegen's ecological theory of motion sickness (Riccio & Stoffregen, 1991; Stoffregen & Riccio, 1988; Stoffregen & Riccio, 1991), and the oculomotor theory (Ebenholtz, 1992). Although these theories argue different causal factors, they all attempt to describe the effects of maladaptation that occur when sensing real or perceived motion. The most prevalent causal theory of motion sickness, the "Sensory Conflict Theory," was proposed in 1975 (Reason & Brand, 1975b). The sensory conflict theory hypothesizes that sensory inputs to the brain, mainly from the visual system and the vestibular system (including other senses such as somatosensory input) are in disagreement or are different than sensations experienced in the past. The resulting conflict is thought to provoke motion sickness. Visual modifications to perception such as time delays found in video displays or virtual environments, create situations whereby the visual images we are observing are not the same as those we have learned and mapped during development, and thus are potential sources of sensory conflict. These sensory conflicts routinely cause motion sickness symptoms, in fact, collectively, motion sickness symptoms cause up to 17% of participants to withdraw from experiments using virtual environments (Lawson, 2014).
Motion Sickness in HMDs

Sixty-one to eighty percent of participants report motion sickness symptoms during experiments employing a virtual environment (Lawson, 2014). Symptoms normally arise from several sources, including optical and temporal distortions. Often these distortions are accompanied by an alteration of the expected inputs between the visual and vestibular systems (McCauley & Sharkey, 1992). Motion sickness caused by optical and temporal distortions has been widely investigated as a result of the increased use of simulators in aviation (Gower Jr. & Fowlkes, 1989; Kennedy & Fowlkes, 1992; Kennedy, Lane, Berbaum, & Lilienthal, 1993; Kennedy & Lilienthal, 1989). In fact, the term "simulator sickness" is used to describe the motion sickness-like symptoms observed during exposure to simulators (Kennedy & Lilienthal, 1989). Research also points to the validity of using simulator sickness measurements such as the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993) to measure (Bruck & Watters, 2011) and to report motion sickness symptoms during simulator and virtual environment exposures. Sickness during virtual reality exposure to computer generated environments (Davis et al., 2014; McCauley & Sharkey, 1992) is referred to as "cybersickness". Despite evidence that simulator sickness and cybersickness are somewhat different (Stanney, Kennedy, & Drexler, 1997; Stanney, Mourant, & Kennedy, 1998), the terms are often used interchangeably. To minimize confusion, these symptoms will be referred to using the broader term motion sickness throughout the remainder of this document.

During exposure to HMD systems, motion sickness symptoms may be related to system time delay or lag, which are collectedly referred to as system latency.
System Latency

Update delay or system latency is the time it takes for a real-world event to be sensed, processed, and displayed to the user. Latency is commonly in the range of tens to hundreds of milliseconds (ms) and causes control problems for users. In virtual reality systems, latency has been shown to confound tasks where timing is critical to successful task completion, such as pointing and object motion tasks (Teather, Pavlovych, Stuerzlinger, & MacKenzie, 2009), catching tasks (Lippi, Avizzano, Mottet, & Ruffaldi, 2010), and ball bouncing tasks (Morice, Siegler, & Bardy, 2008). In robotics, latency has an impact on teleoperation and remote manipulation because of visual display limitations and delayed feedback (Colin Ware, 1994; Liu, Hoover, & Walker, 2004). Delayed feedback can slow reaction-times of the virtual display user, thereby decreasing the user’s ability to perform tracking and pursuit tasks (Foulkes & Miall, 2000; Keele & Posner, 1968). This delay in feedback creates a conflict because users cannot reliably use feedback from their current actions to correct their current behavior. Its effect has also been studied in immersive video conferencing where the introduction of latency between parties in a conversation has been shown to cause frustration and confusion when audio and video images were not synchronized (Roberts, Duckworth, Moore, Wolff, & O’Hare, 2009).

Some authors have suggested that it is critical for latency values to be below the 16-80 ms range (Vincenzi et al., 2011). However, there is little research evidence to support a critical threshold at which latency is no longer an issue. Latency is thought to cause an increase in motion sickness symptoms for some individuals. However, when
Moss and Muth (2011) isolated latency from other system variables, varying the amount of added HMD system latency resulted in no increase in motion sickness symptoms. As this finding was somewhat contradictory in nature to other literature on system latency, they recommended further investigation of possible interactions of latency and other system factors (Moss & Muth, 2011). These recommendations informed subsequent studies (described below) that explored system latency in greater detail. Often, system latency in HMDs is reported as a constant value. However, recent research from our lab showed that system latency varies, fluctuating in both rate and magnitude (Wu et al., 2013). These fluctuations in latency are the source of the perceptual modifications investigated in this study.

**Frequency and Amplitude of Latency**

Wu, et al. (2013) found that latency associated with HMDs is variable, fluctuating in both frequency and amplitude due to a drift in sensor error. 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, measured in milliseconds. Latency was found to drift in frequency within the range of 0.5 to 1.0 Hz with measured oscillations in amplitude of around 20-100 ms. St. Pierre et al. (2015) examined how differences in the characteristics of varying latency affected the motion sickness symptoms in HMD users. St. Pierre manipulated the system latency of an HMD to create four different latency conditions. Condition 1 was the base system latency condition, consisting of base system latency of 70 ms. Condition 2 was the constant condition, consisting of base system latency plus 200 ms (270 ms total). Condition 3 was
the fixed condition, consisting of fixed frequency, fixed amplitude latency consisting of base system latency plus 100 ms of constant latency and 100 ms of latency varying at 0.2 Hz (270 ms total) depicted in Figure 1.1 below. Condition 4, the varying condition, consisting of base system latency plus 100 ms of added latency, plus randomly varying latency between 20 and 100 ms at 0.2 Hz (70-270 ms total) depicted in Figure 1.2 below (St. Pierre, Banerjee, Hoover, & Muth, 2015).

St. Pierre, et al., (2015) found that users reported greater motion sickness in the randomly varying-amplitude-of-latency condition, than either the base or the added-constant-amplitude-of-latency conditions. This work was refined by Kinsella (2016), confirming St. Pierre, et al.’s (2015) earlier results, while providing additional evidence that a 0.2 Hz frequency of latency condition provoked increased symptoms compared to 1.0 Hz frequency of latency. This is noteworthy because sea state frequencies around 0.2 Hz have been found to be highly provocative of motion sickness (Golding, Mueller, & Gresty, 2001). To date, the research in our laboratory has only explored subjective symptoms of sickness and not explored the effects of varying system latency on human performance.
Figure 1.1. Graph of 70 ms base system latency with 0.2 Hz frequency plus 100 ms amplitude varying latency.

Figure 1.2. Graph of 70 ms base system latency with 0.2 Hz frequency plus 20-100 ms varying amplitude varying of latency.

Overview of the Present Study

The present study builds on the work of Moss, St. Pierre and Kinsella, all of whom studied in this lab using a common object location task developed by Moss and
Muth (2011). The object location task has participants stand in a marked area and visually identify 8 objects arrayed across a 180-degree arc. In the previous works, participants were provided with a handrail for support and asked to limit their torso rotation, locating objects only via their head movements. In the current work, the handrail was removed as a targeting task was added to the object location task, requiring participants to use a handheld laser pointer to illuminate targets co-located with the 8 objects previously described by Moss and Muth (2011). This modified version of the task generates an objective performance score based on the number of targets hit during each two-minute block of trials and the time necessary to achieve each hit. The targeting task was chosen for its low cost, face validity and generalizability to future HMD uses. Two latency conditions were examined representing the least and most sickening conditions from the previous work in the lab: a base system latency condition of 70 ms latency with no variation in latency, hereafter referred to as “constant latency”; and base system latency plus randomly varying amplitude of latency between 20 and 100 ms at 0.2 Hz, hereafter referred to as “varying latency”.

**Hypotheses**

The hypotheses were divided into two main areas: motion sickness and targeting task performance. Three motion sickness results were hypothesized. A main effect of condition was hypothesized such that individuals in the constant latency condition would report fewer simulator sickness symptoms than in the varying latency condition. A main effect of time was hypothesized such that during repeated exposures to the stimulus, both conditions would produce an increase in reported symptom scores across the blocks of
trials. An interaction between condition and time was hypothesized such that there would be a greater increase in sickness score over time for the varying latency condition. These hypotheses were based on the findings of St. Pierre, et al., (2015) and Kinsella (2014).

Three hypotheses corresponding to accuracy and three hypotheses corresponding to task completion time were developed for the targeting task. For accuracy (the number of hits), a main effect of condition was hypothesized such that more targets would be hit in the constant latency condition than in the varying latency condition. A main effect of time was hypothesized such that during repeated exposures to the stimulus both conditions would show a decrease in the number of targets hit. An interaction between condition and time was hypothesized such that there would be a smaller number of targets hit over time for the varying latency condition. For task completion time (time-to-hit), a main effect of condition was hypothesized such that there would be a decrease time-to-hit in the constant latency condition than in the varying latency condition. A main effect of time was hypothesized such that during repeated exposures to the stimulus both conditions would show an increase in the time-to-hit. An interaction between condition and time was hypothesized such that there would be increasing time-to-hit values over time for the varying latency condition. These hypotheses were based on the negative effects that motion sickness has been found to have on human performance (Kennedy, Drexler, & Kennedy, 2010).
CHAPTER II

Methods

Participants

Thirty participants were recruited from Clemson University’s student, staff and faculty population. Participants were recruited via flyers and the Department of Psychology human subject pool that is managed by the use of a software management system. Participants were paid $15 for their first session and $35 for their second session to encourage attending both of the experimental sessions. Student participants were also given extra course credit for their participation where appropriate. All participants received compensation/course credit regardless of their level of participation in the experimental trials. Individuals who self-reported any history of brain, heart, stomach, eye (other than corrected vision), inner ear problems, or who were pregnant, were not eligible for participation. Individuals with corrected vision were required to wear contact lenses to participate due to the limitations of the HMD used in this experiment.

Design

Lawson (2014) recommends the use of a repeated measures design in motion sickness studies when the number of sessions is low (under 4) to reduce between-subjects’ variability in motion sickness susceptibility. Therefore, the current study employed a 2 (latency) X 5 (blocks of trials) within-subjects design. In addition, during each experimental condition, participants performed an additional set of five training blocks of trials without being exposed to the experimental manipulation, i.e., they were not wearing the HMD. Stern and colleagues reported no evidence of adaptation to a
rotational stimulus when sessions were scheduled between 4 and 24 days apart (Stern, Hu, Vasey, & Koch, 1989). Further, Lawson (2014) recommends that investigators schedule sessions at least one week apart to minimize possible adaptation effects. Therefore, experimental sessions were scheduled two weeks apart to minimize these effects. The independent variables were system latency with two levels, constant latency and varying latency as defined above, and block, consisting of five blocks of 40 trials each. Three main dependent variables were examined: sickness; accuracy; and time-to-hit. Sickness scores were obtained using the simulator sickness questionnaire (SSQ) (Kennedy et al., 1993) and the Motion Sickness Assessment Questionnaire (MSAQ) (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001). Accuracy and time-to-hit were measured by the number of laser targets hit and the number of seconds needed to score a hit. Both accuracy and time-to-hit were obtained via custom software written to capture these data. Participants were balanced for gender and randomly assigned to one of the two counterbalanced order of conditions, constant latency first or varying latency first. Previous studies employing the object location task used N=30 participants per condition, therefore a similar sample was chosen for this study to enable comparisons between datasets. A complete diagram of the experiment is shown in table 2.1 below.
Table 2.1. The within-subjects study design used for this research.

<table>
<thead>
<tr>
<th>Surveys</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Block 4</th>
<th>Block 5</th>
<th>Pre</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Block 4</th>
<th>Block 5</th>
<th>Post</th>
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<tbody>
<tr>
<td>Consent</td>
<td>40 trials</td>
<td>40 trials</td>
<td>40 trials</td>
<td>40 trials</td>
<td>40 trials</td>
<td>MSAQ</td>
<td>40 trials</td>
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<td>(doff HMD)</td>
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<tr>
<td></td>
<td>10</td>
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<td>2</td>
<td>3</td>
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</table>

Total Time Part 1 = 23 mins
Total Time Experimental Session 1 = 45 mins
14 Day Break

<table>
<thead>
<tr>
<th>Surveys</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
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<th>Pre</th>
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</tbody>
</table>

Total Time Part 1 = 13 mins
Total Time Experimental Session 2 = 35 mins.
Colors: Experimental Sessions | Task without HMD | Task With HMD

Materials and Apparatus

**Head-Mounted Display.** A *ProView*™ XL 50 HMD (Kaiser Electro-Optics, Inc.) was used for this experiment as shown in Figure 2.1. The XL 50 is a binocular 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. The HMD has a 50° field of view (FOV) diagonally, 30° FOV vertically, and 40° FOV horizontally. It weighs 35 oz prior to camera being mounted.
Digital Camera. A Uniq UC-610CL™ color digital CCD camera was used to capture images of the lab. This camera was mounted atop the HMD as shown in Figure 2.1. The camera resolution was 659 x 494 active pixels at a frame rate of 110 Hz. The camera had a C-mount lens platform and used a 1/3” progressive scan CCD imager with R, G, and B primary color mosaic filters. The camera weighed 200 grams.

Camera Lens. The C-mount lens used in the study was a 1/2” format, Edmonds Optics™ model 67709. The focal length was 6 mm, with an aperture of F=1.4. This lens was chosen to optimize the scene presented to the wearer. See the full discussion of Geometric Field of View provided by Moss and Muth (Moss & Muth, 2011).

Frame Grabber. A Dalsa X64 CL Express™, 256Mb PCI camera link frame grabber card for image capture was installed on a Windows XP computer containing a 3.6 Ghz Intel® Core™ i3-4160 CPU and 8 GB of RAM. This card powered the camera and supplied images to the update delay software. The captured images from the camera
were projected on the HMD after manipulation, with a single image being presented to both eyes.

**Update Delay Software.** The manipulation of system latency was made possible by an in-house program described by Kinsella (2014) and St. Pierre, et al., (2015). The delays used in this study were validated by the outside observer method (Wu et al., 2013) prior to beginning the study.

**Object Location Task.** The object-targeting task first required participants to visually locate one of eight objects in the laboratory. The order of presentation of the objects was the same as used by Moss and Muth (2011). Each experimental session consisted of 200 randomized head movements blocked into five, two-minute blocks of 40 trials each (Moss, 2008). The 5 blocks were then repeated for both the training and the experimental portions of each of the two conditions. In this way, participants consistently received an identical pattern of trials for the training and experimental portions of both conditions. However, with such a high number of trials across the five blocks (200 trials), it would be nearly impossible for a participant to figure out the repeated pattern. A complete listing of all of the objects presented by the blocks of trials is located in Appendix G. The layout of the room is shown in Figure 2.2. The objects, shown in Figure 2.3, were: scale (A), clock (B), flag (C), fire (D), hall (E), cross (F), fan (G), and shelf (H). The names of the targets were changed slightly from previous studies to monosyllabic descriptive names to facilitate timing in the scoring software.
Figure 2.2. Footprint of room layout for the object location and targeting task.

Figure 2.3. Pictures of the 8 objects comprising the object location and targeting task during experimental sessions.
**Targeting Task.** Laser targets were co-located with each of the 8 visual objects described in the section Object Location Task section and can be clearly seen in Figure 2.3 above. A hand-held laser pointer, (Laser 301, Red Laser Pointer Pen G301, 650 nm, 0.2 W), was used as a pointing device. Laser targets (Cheap Shot™ Laser Target, Impulse USA, Inc., PO Box 193, St. Louis, MO 60310) were used as aiming points. The laser target responds to a hit by the momentary illumination of 6 LEDs surrounding the target. The targets were modified to emit a 330 Hz tone at approximately 90 db simultaneously with the illumination of the lights on the target. The laser pointer and the targets are shown in Figure 2.4 below. Participants scored a hit by “hitting” the target with the laser pointer during a fixed time interval, beginning when the target was announced and ending when the subsequent target was announced (approximately 3 seconds). Failure to illuminate the target during this time interval constituted a miss.
Figure 2.4. The Laser 301 laser pointer (left) and Cheap Shot Laser Target modified with 330 Hz buzzer (right) used in this experiment.

The maximum horizontal movement required by the stimulus arrangement was 180°. The minimal horizontal movement required by the stimulus arrangement was 35°. Participants were instructed to make movements with only their head and neck. If necessary, slight shoulder movements were allowed, but participants were instructed to minimize hip or leg movements during the task.

**Task Automation.** The current task paradigm incorporated custom computer code to present the stimuli automatically for the object location and targeting tasks using a computerized text-to-speech voice program. Provisions were made to administer the MSAQ and SSQ automatically when required during the experimental protocol, or manually if necessary. Laboratory audio was continuously monitored via a microphone during the experimental sessions. The software parsed the audio file in real-time and
computed the amount of time between the announcement of the target and the activation of the buzzer indicating a hit. Time for each buzzer activation was written to a comma-separated values file (.csv) file automatically for post experimental analysis. In absence of a buzzer (indicating a miss), the software inserted a value of -1 (as a marker), into the file. These values were replaced with a time of 3 seconds (representing the maximum amount of time allowed to score a hit) during the data analysis.

The data resulted in two dependent variables used to measure performance. The first performance measurement was accuracy, derived by determining the number of hits scored during each block of trials. The second measurement was time-to-hit, derived by summing the times needed to score for each hit, plus 3 seconds for each miss in each block of trials. The total seconds for each block of trials was divided by 40 (number of trials) to produce a rate (seconds per hit) for analysis. This automation effort ensured that each experimental session was identical in order to minimize experimenter effects.

**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, 1975b). 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. The MSHQ was included in this
experiment to enable comparisons with data from previous experiments using this paradigm.

**Motion Sickness Susceptibility Questionnaire.** The Motion Sickness Susceptibility Questionnaire – Short Version (MSSQ-S) (J. F. Golding, 2006) is a simplified edition of Reason and Brand's Motion Sickness History Questionnaire (MSHQ) described below. It consists of two scales, the MSSQ-A for childhood motion sickness experience and the MSSQ-B for adult motion sickness experiences. Each section reports the frequencies of nausea and vomiting during nine motion related situations. A four-point scale ranging from "never" to "11 times or more" is used weight the nausea and vomiting scores. Scores range from 0 to 180, with a larger score indicating a greater susceptibility to motion sickness. The predictive validity of the questionnaire exceeds that of the long version of this questionnaire as well as the MSHQ.

**Simulator Sickness Questionnaire.** The Simulator Sickness Questionnaire (SSQ) is a measure of motion sickness symptoms in a simulated virtual environment (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, and 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 235.6 (15.4 when square root transformed). The creators of the questionnaire stated SSQ scores from 5-10 (2.2-3.2 when square root transformed) indicate minimal symptoms, 10-15 (3.2-3.9 when square root transformed) indicate
significant symptoms, and scores above 20 (4.5 when square root transformed) indicate simulator that produces too much sickness (Kennedy et al., 2003).

**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 was 144. The MSAQ was included to enable comparisons with previous research using this paradigm.

**State-Trait Anxiety Inventory.** The State-Trait Anxiety Inventory (STAI) is a 40-item psychological battery developed by C.D. Spielberger, R.L. Gorsuch, and R.E. Lushene. The test is divided into two 20-question sections. The Trait Inventory measures predisposition to stress, worry and discomfort. The State Inventory measures the temporary arousal of the autonomic nervous system induced by situations perceived as threatening or dangerous. Each inventory is scored using a 4-point, forced-choice Likert Scale from 1 (low) to 4 (high) resulting in a score for each part ranging from 20 to 80 with lower numbers indicating less anxiety (Spielberger, Gorsuch, & Lushene, 1970).

**Procedure**

Upon arrival, each participant received a copy of the Clemson University Institutional 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, pregnancy, vertigo, and past experience with virtual environments and/or
HMDs using self-report methods. Any participants answering yes to the previous screening questions were not permitted to participate in the experiment. Participants were then administered the MSHQ and the MSSQ-S. Both questionnaires were scored after the completion of the study and were not used to assess their motion sickness history and susceptibility to motion sickness prior to the study. Individuals who reported a severe history of motion sickness, e.g., experiencing motion sickness symptoms frequently or easily were excluded from the study. Participants not excluded were randomly assigned to condition order of either the constant latency first or the varying latency condition first and scheduled for their second experimental session prior to being escorted to the laboratory for the experiment. The day of the week and time of day for each session was kept the same in order to minimize circadian influences between experimental sessions. When both sessions were complete, the experimenter debriefed the participants on the purpose of the experiment.

**Task Training**

The number of trials needed to train the targeting task was determined through pilot testing. Seven subjects each performed 30 blocks of 40 trials of the targeting task, consisting of 1,200 trials over a two-day period. During the first day, the participants performed 15 blocks of trials (600 total trials). Participants returned to the lab the following day for an additional 15 blocks of trials (600 total trials), completing the 1,200 trial pilot test. Each subject was presented the same set of randomized targets and observers recorded their performance manually. Participants averaged 92% (37/40) accuracy on their first block of trials, increasing their accuracy to 96.25% (38.5/40) by
the end of the fifth block of trials in the first session, remaining above 38 hits for the remainder of the pilot testing. When repeating the 15 blocks of trials on the second day, participants averaged 97.5% (39/40) level of accuracy. Based on these results, all participants were given a five, 40-trial blocks of training prior to each experimental session in order to eliminate training effects during this study. Graphs from the pilot study are located in Appendix Q.

All participants began each condition by first learning or re-learning the targeting task. They were asked to stand in a marked area 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 and cause fainting (van Dijk et al., 2005). Computer software provided each target name and its direction relative to the previous object (e.g. right, clock). The experimenter demonstrated the use of the laser pointer and how to engage the laser targets. The laser pointer was activated by pressing a 5 mm button on the body of the laser pointer. To activate the targets, a 10 mm white button in the center of the target had to be hit with a laser pulse at a rate less than 1 Hz. Target activation was signaled by the activation of 6 LED lights surrounding the target as well as an audio tone, see Figure 2.4.

**Experimental Sessions with the HMD**

Participants next completed the experiment with the HMD. To begin the experimental session, the HMD displays were adjusted to match the subject’s interpupillary distance (IPD) by measuring the distance between the participant's eyes (in centimeters) with a steel ruler. The HMD lenses were then adjusted a setting corresponding to the participant’s IPD measurement. Next, the participant was guided
through donning and adjusting the HMD fit. When the participant indicated the HMD was adjusted appropriately, the MSAQ was administered followed by the SSQ.

Participants then performed the object location and targeting tasks described above, repeating the five blocks of two-minute trials. At the end of each block of trials, the participants were administered the SSQ. After the final block of trials, the experimenter again immediately administered the SSQ and MSAQ before the participant removed the HMD.

Participants were instructed that the goal of the experiment was not to make them feel too uncomfortable and that if at any time they felt their comfort level prevented them from continuing that they should inform the experimenter and the study would be stopped immediately. Additionally, the experimenter monitored the participant's responses during the administration of the SSQ for levels of sickness. If the participants reported any symptoms of “severe” on the SSQ, the experimenter asked participants if they felt they could continue with the experiment. The study was terminated if the participant indicated they could not continue, took action to physically remove the HMD, or did not respond to verbal questions. Otherwise, all blocks of trials were completed. If the participant responded that they could not continue, the experimenter quickly removed the HMD from their head and helped them to a chair adjacent to where the participant was standing. In these cases, the experimenter administered the SSQ and MSAQ after the participant was seated and safe. In cases of early termination, participants were offered water and were monitored until they felt better, then administered a final SSQ to verify reduced symptoms prior to releasing the participant. In all other cases, upon successful
completion of the five blocks of experimental trials, the participants were assisted in
doffing the HMD after the final administration of the MSAQ and the SSQ. All
participants received full compensation regardless of their participation level in the study.

**Planned Data Analysis**

Sickness levels were assessed with both the SSQ (assessed during pre-trial, after
each block of trials and post-trial) and the MSAQ (assessed pre-trial and post-trial).
Because the SSQ assessed sickness at key points throughout the study, it was used as the
main indicator of sickness levels in the main statistical analyses. An analysis of sickness
levels using the MSAQ can be found in Appendix P.

Though SSQ data are thought by many researchers to be ordinal, there is
precedent in the motion sickness literature to treat SSQ data as interval data and to
perform analyses with parametric techniques (Sharples, Cobb, Moody, & Wilson, 2008;
Young, Adelstein, & Ellis, 2007). Prior to performing any statistical analyses,
distributions of SSQ scores and performance variables were examined for normality and
homogeneity of variance. In cases where distributions were found to be non-normal,
appropriate transformations were sought. Distributions were again examined for
normality after the transformation to insure that the assumptions were met before
performing parametric statistical analyses.

Repeated measures analysis of variance (ANOVA) were then used to evaluate
sickness (SSQ scores used as interval data), accuracy based on the number of targets hit,
and time-to-hit based on total time needed for activating targets within a block of 40
trials. For sickness, accuracy and time-to-hit data, each participant completing an experimental session had five total scores, corresponding to each block of trials.

In addition, the SSQ scores for each condition were examined to determine when each participant experienced peak symptoms and the number of hits at the peak SSQ and time-to-hit at the peak SSQ scores were also included in the planned analyses and compared using paired samples $t$-tests.

Correlational analyses were planned to examine the relationships between sickness, accuracy and time-to-hit. These analyses included: between subjects; between subjects by condition; within-subjects; and within-subjects by condition.
CHAPTER III

Results

Data were collected during two experimental sessions. Of the 30 (15 male) participants in the study, one female participant did not return for the second experimental session and her data were omitted from analyses, the demographics of the remaining 29 participants are shown in Table 3.1 below.

Table 3.1. Demographics of participants.

<table>
<thead>
<tr>
<th>N</th>
<th>Gender</th>
<th>Age M(SD)</th>
<th>Race C/B/H</th>
<th>Hand R/L</th>
<th>MSSQ (Percentile) M (SD)</th>
<th>STAI Trait M (SD) (20-80)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>F</td>
<td>19.57(2.10)</td>
<td>13/1/0</td>
<td>10/4</td>
<td>35.4 (27.7)</td>
<td>34.4 (7.3)</td>
</tr>
<tr>
<td>15</td>
<td>M</td>
<td>20.21(2.08)</td>
<td>13/1/1</td>
<td>13/2</td>
<td>19.3 (20.2)</td>
<td>33.3 (7.7)</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>19.96(2.17)</td>
<td>27/2/1</td>
<td>23/6</td>
<td>27.4 (24.9)</td>
<td>33.8 (7.4)</td>
</tr>
</tbody>
</table>

There were no differences noted between the male and female groups for age, race, handedness, or trait anxiety. There was a significant difference in the MSSQ-S scores between the male and female groups such that the female group reported significantly higher motion sickness susceptibility scores than the male group, \( t(23.7) = 1.71, p = .05 \) (1-tailed), \( d = 0.68 \). Levene's test indicated unequal variances \( (F=5.4, p = .03) \), so degrees of freedom were adjusted from 27 to 23.7 in this comparison.

Withdrawals During Experimental Sessions

Twenty-nine participants contributed 58 total experimental sessions (2 conditions X 29 participants). During these sessions, 2 participants (1 male) withdrew themselves from the first experimental session prior to completing all 5 experimental blocks,
reporting high levels of dizziness, increased nausea, moderate to severe headache and moderate to severe eyestrain symptoms. Both participants suffered these symptoms during their first experience in the HMD (although in different latency conditions) and both participants returned to the lab and completed all trials in the other condition with no issues. The male participant's symptoms developed after completing 4 out of 5 blocks of trials during the varying latency condition, while the female's symptoms developed after completing the first block of trials during the constant latency condition. All withdrawals were during break periods after the administration of the SSQ. Peak SSQ, MSAQ, the number of hits and time-to-hit data were collected from these individuals and their data were included in analyses based on peak SSQ Scores, but excluded from analyses of participants' performance over time. Because of the low withdrawal rate, no further analyses were performed on withdrawals by condition.

When participants’ SSQ responses included a rating of “severe”, the experimenter asked if the participant could continue with the next block of trials. There were a total of 34 “severe” ratings by 5 separate participants. In only one instance did a participant elect to stop when asked if they were able to continue the trials. Additionally, one participant accounted for 50% (17/34) of the “severe” responses, but never stopped the trials. The most common “severe” responses were: Difficulty Concentrating (7); Difficulty Focusing (6); Blurred Vision (5); and Sweating (4).

**Sickness Levels**

Sickness levels were based on the participants' peak SSQ scores. The results of the Shapiro-Wilk normality test indicated that the peak SSQ scores were not normally
distributed, $W(58) = .903, p < .01$, as shown in Figure 3.1 below. No outliers were identified.

![Histogram of Peak SSQ scores](image)

**Figure 3.1** Histogram of Peak SSQ scores for both conditions for all 39 participants showing positive skewness.

To correct the normality issue, a square root transformation (Bland & Altman, 1996) was performed on the peak SSQ data to adjust for the skewness and kurtosis, resulting in a normal distribution of peak SSQ scores, as can be seen in Figure 3.2 below. All further analyses using SSQ data were performed using the transformed values (SQRT(SSQ)). The data were next analyzed to determine if the participants were in fact, sick.
Figure 3.2 Histogram of Peak SSQ scores after the square root transformation for all 29 participants for both conditions, showing a normal distribution.

**Levels of Overall Sickness.** To determine the level of sickness obtained during the experimental sessions, the pre-trial SSQ scores were compared to the peak SSQ scores recorded during the blocks of trials for all 29 participants in both latency conditions. Using the symptom categorization criteria established by Kennedy et al. (2003), the participants began at the study at the marginal sickness level (< 3.24) with a mean pre-trial SSQ score of $M = 3.17$ ($SD = 3.02$) and progressed to highest category, the problematic level (> 4.47) with a mean peak SSQ score of $M = 6.11$ ($SD = 3.34$). The
pre-trial and peak sickness scores were compared using a paired-samples $t$-test and found to be significantly different, $t(57) = 9.55, p < .01$ (1-tailed), $d = .92$.

**Levels of Sickness by condition.** The levels of sickness obtained during each latency condition were also analyzed. During their exposure to the constant latency condition the participants reported marginal sickness levels after the training session but before the experimental session ($< 3.24$) with a mean pre-trial SSQ score of $M = 3.23$ ($SD = 2.92$) and progressed to problematic levels ($> 4.47$) with a mean peak SSQ score of $M = 5.90$ ($SD = 3.27$) during the experimental session. The pre-trial and peak sickness scores were compared using a paired-samples $t$-test and found to be significantly different, $t(28) = 5.95, p < .01$ (1-tailed), $d = .86$. During their exposure to the varying latency condition the participants reported marginal sickness levels after completing the training session, but before completing the experimental session ($< 3.24$) with a mean pre-trial SSQ score of $M = 3.13$ ($SD = 3.17$) and progressed to problematic levels ($> 4.47$) with a mean peak SSQ score of $M = 6.31$ ($SD = 3.45$) during the experimental session. The pre-trial and peak sickness scores were compared using a paired-samples $t$-test and found to be significantly different, $t(28) = 7.58, p < .01$ (1-tailed), $d = .96$.

It is important to point out that in all conditions, reported symptom levels reached above the problematic level of greater than 4.4 ($\text{SQRT(SSQ)}$) for simulators inducing significant sickness (Kennedy et al., 2003).

**Stimulus Order Effects.** Peak SSQ scores were examined to determine if there was an effect of stimulus order. A paired samples $t$-test comparing the peak SSQ scores
between the first and second experimental sessions, regardless of condition, showed no significant differences in peak SSQ scores, $t(28) = .79, p = .44$ (2-tailed), $d = .06$.

**Gender Differences in Sickness Levels.** To analyze the potential differences in sickness susceptibility by gender, an independent samples t-test was used to evaluate peak SSQ scores. The results show that there was no difference between female ($M = 6.23, SD = 3.42$) and male ($M = 5.59, SD = 3.21$) peak sickness levels in the constant latency condition, $t(27) = .52, p = .30$ (1-tailed), $d = .19$, or between female ($M = 6.59, SD = 3.15$) and male ($M = 6.05, SD = 3.80$) peak sickness scores in the varying latency condition, $t(27) = .41, p = .34$ (1-tailed), $d = .16$.

**The Effects of Latency on Sickness**

To examine the effects of condition on sickness, a paired-samples $t$-test (directional according to the hypotheses) was performed comparing peak SSQ scores between the constant and varying latency conditions. Including all participants, during their exposure to the constant latency condition participants reported a mean peak SSQ score of $M = 5.90$ ($SD = 3.27$) and during their exposure to the varying latency condition the participants reported a mean peak SSQ score of $M = 6.31$ ($SD = 3.45$) a marginally significant difference, $t(29) = -1.58, p = .06$ (1-tailed), $d = .60$. The analysis was repeated after removing 3 participants who reported experiencing no symptoms in either trial, a paired-samples $t$-test (directional according to the hypotheses) was conducted using peak SSQ scores between the constant ($M = 6.51, SD = 2.86$) and varying latency ($M = 7.04, SD = 2.83$) conditions yielding significant results, $t(26) = -1.94, p = .03, d = .18$. See Appendix I for a complete analysis with the data from these participants removed.
The effects of added frequency and amplitude of latency on peak SSQ scores were further assessed with a 2 (HMD condition) X 6 (block) Repeated Measures ANOVA. A significant effect of block was found, $F (5,50) = 13.76, p < .01, \eta^2_p = .58$, such that sickness levels increased over each block. There was no significant effect of condition, $F (1,54) = 0.10, p = .75, \eta^2_p = .00$ and no evidence supporting an interaction between condition and block $F (5,50) = 0.39, p = .85, \eta^2_p = .04$. A graph of SSQ across the blocks by condition is shown in Figure 3.3 below.

Figure 3.3 Sickness scores (square root of SSQ) shown per block of trials showing that sickness increases over block of time and varies by condition. Constant latency is labeled “Baseline Latency” in the graph above.
The Effects of Latency on Performance

The effects of added amplitude and frequency of latency on performance were analyzed by examining two measures, accuracy and time-to-hit. As with the SSQ data, the distributions of both accuracy and time-to-hit were examined across the blocks. In all cases the data were found to be normally distributed with equal variances. An examination of the effects of condition and block of trials was conducted for both accuracy and time-to-hit.

Accuracy. A 2 (HMD condition) X 5 (block) repeated measures ANOVA was used to examine the effects of latency on accuracy. As can be seen in Figure 3.4 below, a significant effect of condition was found, $F(1, 54) = 35.20, p < .01, \eta^2_p = .40$, with lower accuracy in the varying latency condition compared to the constant latency condition. A significant effect of block was also found in which accuracy increased over each block, $F(4, 51) = 13.50, p < .01, \eta^2_p = .52$. There was no evidence supporting an interaction between condition and block $F(4, 51) = 1.65, p = .18, \eta^2_p = .12$. 


Figure 3.4 The performance measurement "accuracy" showing an increase in number of hits over time and differences between latency conditions. Constant latency is labeled “Baseline Latency” in the graph above.

**Time-to-hit.** A 2 (HMD condition) X 5 (block) repeated measures ANOVA examined the effects of latency on time-to-hit. As shown in Figure 3.5 below, a significant effect of condition was found, $F (1,53) = 53.34, p < .01, \eta^2_p = .98$, with slower time-to-hit in the varying latency condition compared to the constant latency condition. A significant effect of block was also found such that the time-to-hit the target improved across blocks of time, $F (4,50) = 34.34, p < .01, \eta^2_p = .73$. There was no evidence of an interaction between condition and block, $F (4,50) = 0.61, p = .66, \eta^2_p = .05$. 
Figure 3.5 The performance measurement "time-to-hit" showing number of seconds required to score a hit per block of trials and differences between conditions. Constant latency is labeled “Baseline Latency” in the graph above.
Correlational Analyses

A series of Pearson’s product-moment correlational analyses were used to examine the relationship between sickness, accuracy and time-to-hit. In order to gain a better understanding of the data, the correlations between sickness, accuracy and time-to-hit were examined at four different levels: between subjects; between subjects by condition of latency; within-subjects; and within-subjects by condition of latency.

**Between-subjects analysis.** The data were first examined at the between-subjects level. Correlations of sickness and accuracy; sickness and time-to-hit; and accuracy and time to hit are included below. Condition was ignored and each participant contributed two data points to the analysis resulting in a total $N=58$.

**Sickness and accuracy.** The analyses began with a scatterplot of the between-subjects data for sickness and accuracy, as shown in Figure 3.6 below. The number of hits were negatively correlated with sickness, Pearson's $r (58) = -.31, p = .01$, indicating that as sickness increased, accuracy decreased.
Figure 3.6 Scatterplot of sickness and accuracy showing that as sickness increases, accuracy decreases.
**Sickness and time-to-hit.** A scatterplot of sickness and time-to-hit is shown in Figure 3.7 below. Time-to-hit was positively correlated with sickness, Pearson's $r$ ($58$) = $0.35$, $p < 0.01$, indicating that as sickness increased, the time-to-hit increased.

![Scatterplot of Sickness and Time-to-Hit](image_url)

*Figure 3.7 Scatterplot showing the positive relationship between sickness and time-to-hit.*
**Accuracy and time-to-hit.** A scatterplot of the number of hits and time-to-hit is shown in Figure 3.8 below. There was a strong negative correlation between time-to-hit and accuracy, Pearson's $r$ (58) = -.94, $p < .01$, indicating that as accuracy decreased the time-to-hit increased.

![Scatterplot of Accuracy and Time-to-Hit](image)

*Figure 3.8 Scatterplot showing the strong negative relationship between accuracy and time-to-hit.*
**Between Subjects by Condition.** Next, the between-subjects relationships were examined within each condition of latency. In this analysis, each participant contributed one data point to the two separate sets of correlations by condition. Therefore, N= 29 by condition. Correlations of: sickness and accuracy; sickness and time-to-hit; and accuracy and time to hit are included below.

**Sickness and accuracy.** A scatterplot of sickness and accuracy by condition is shown in Figure 3.9 below. For both latency conditions, accuracy was negatively correlated with sickness. In the constant condition, Pearson's \( r(29) = -.38, p = .02 \) and in the varying latency condition, Pearson's \( r(29) = -.33, p = .04 \), indicating that as sickness increases, accuracy decreases for both conditions.

![Scatterplot of Sickness and Accuracy](image)

*Figure 3.9 Scatterplot of sickness and accuracy by condition of latency. Constant latency (labeled “Base Latency”) is shown on the left and varying latency on the right. Both graphs show that as sickness increases, the number of hits decreases.*
**Sickness and time-to-hit.** A scatterplot of sickness and time-to-hit by condition is shown in Figure 3.10 below. For both latency conditions, time-to-hit was positively correlated with sickness. In the constant condition, Pearson's $r (29) = .42, p = .01$ and in the varying latency condition, Pearson's $r (29) = .42, p = .01$, indicating that as sickness increases, time-to-hit increases for both conditions.

![Figure 3.10 Scatterplot of sickness and time-to-hit by condition of latency. Constant latency (labeled “Base Latency”) is shown on the left and varying latency on the right. Both graphs show that as sickness increases, time-to-hit increases.](image-url)
**Accuracy and time-to-hit.** A scatterplot of accuracy and time-to-hit is shown in Figure 3.11 below. For both latency conditions, there was a strong negative correlation between accuracy and time-to-hit. In the constant condition, Pearson's $r$ (27) = -.87, $p < .01$ and in the varying latency condition, Pearson's $r$ (27) = -.94, $p < .01$, indicating that as accuracy decreases, time-to-hit increases for both conditions.

*Figure 3.11 Scatterplot of the number of hits and time-to-hit by condition of latency. Constant latency (labeled “Base Latency”) is shown on the left and varying latency on the right. Both graphs show that as the accuracy decreases, the time-to-hit increases.*
**Within-Subjects.** The Pearson's product-moment correlation coefficients were computed within-subject for each individual across their 10 blocks of trials, ignoring condition. The distributions of the resulting Pearson's $r$ values are presented. In addition, sample scatterplots from an individual participant are included. Correlations of sickness and accuracy, sickness and time-to-hit and accuracy and time to hit were performed.

**Sickness and accuracy.** A sample scatterplot of sickness and accuracy for participant #101 is shown in Figure 3.12 below. Sickness and accuracy scatterplots for all participants are in Appendix K. A boxplot of all Pearson's $r$ correlation values for sickness and accuracy across all 29 participants is provided at the end of this section in Figure 3.15. The mean correlation was -.08.

![Within Subjects Correlations](image)

*Figure 3.12 Scatterplot of sickness and accuracy from participant # 101.*
**Sickness and time-to-hit.** A sample scatterplot of sickness and time-to-hit for participant #101 is shown in Figure 3.13 below. Sickness and time-to-hit scatterplots for all participants are in Appendix L. A boxplot of all Pearson's $r$ correlation values for sickness and time-to-hit is provided at the end of this section in Figure 3.15. The mean correlation was -.24.

![Figure 3.13 Scatterplot of sickness and time-to-hit from participant # 101.](image-url)
Accuracy and time-to-hit. A sample scatterplot of accuracy and time-to-hit for participant #101 is shown in Figure 3.14 below. Accuracy and time-to-hit scatterplots for all participants are in Appendix M. A boxplot of all Pearson's $r$ correlation values for accuracy and time-to-hit is provided at the end of this section in Figure 3.15. The mean correlation was -.78.

![Scatterplot of Accuracy and Time-to-Hit](image)

Figure 3.14 Scatterplot of accuracy and time-to-hit from participant #101 showing the strong negative correlation between accuracy and time-to-hit.
Mean Pearson's r values. Boxplots were chosen as a method to graphically represent the distribution of the within-subjects correlational values. A boxplot of the Pearson's r values from all 29 participants showing the mean correlational values between sickness and accuracy, sickness and time-to-hit and accuracy and time-to-hit is provided in Figure 3.15 below. As computed by IBM SPSS Statistics for Windows (IBM Corp. Released 2013. Version 22.0. Armonk, NY: IBM Corp.), the black line in the box represents the median value, the top and bottom edges of the box represent the 25th and 75th percentile values and the “whiskers” represent 1.5 X Interquartile Range (IQR). Outliers are depicted for values above or below the “whiskers” with two markers. Outliers between 1.5 X IQR and 3 x IQR from the edge of the box are shown with a circle symbol “o”. Outliers more than 3 x IQR from the edge of the box are shown with an asterisk symbol “*”.
Boxplot of Mean Pearson's Correlation Values

Figure 3.15 Boxplot of Pearson's r values averaged across the 29 participants showing the range of the data points for the within-subjects correlation of accuracy and time-to-hit.

**Within-Subjects by Condition.** The Pearson's product-moment correlation coefficients were computed within-subject for each individual across their five blocks of trials, for each condition. The distributions of the resulting Pearson's r values are presented. In addition, sample scatterplots from an individual participant are included. Correlations of sickness and accuracy; sickness and time-to-hit; and accuracy and time to hit were performed.
**Sickness and accuracy.** A sample scatterplot of sickness and accuracy for participant # 101 is shown in Figure 3.16 below. Sickness and accuracy scatterplots for all participants can be found in Appendix K. A boxplot of the distributions of the Pearson's r correlation values for sickness and accuracy is provided at the end of this section. For constant latency values see Figure 3.19 and varying latency values see Figure 3.20. The mean correlations were -.20 and -.03 respectively.

![Within Subjects Correlations: Sickness and Accuracy by Condition of Latency](image)

*Figure 3.16 Scatterplot of sickness and accuracy by condition of latency from participant # 101. The constant latency condition is referred to as “Baseline Latency” in this plot.*

**Sickness and time-to-hit.** A sample scatterplot of sickness and time-to-hit is shown in Figure 3.17 below. Sickness and time-to-hit scatterplots for all participants can
be found in Appendix L. A boxplot of all Pearson's $r$ correlation values for sickness and time-to-hit is provided at the end of this section. For constant latency values see Figure 3.19 and varying latency values see Figure 3.20. The mean correlations were -.24 and -.17 respectively.

![Within Subjects Correlations](image)

**Figure 3.17** Scatterplot of sickness and time-to-hit by condition of latency from participant # 101. The constant latency condition is referred to as “Baseline Latency” in this plot.

**Accuracy and time-to-hit.** A sample scatterplot of accuracy and time-to-hit is shown in Figure 3.18 below. Accuracy and time-to-hit scatterplots for all participants can be found in Appendix M. A boxplot of all Pearson's $r$ correlation values for accuracy and time-to-hit is provided at the end of this section. For constant latency values see
Figure 3.19 and varying latency values see Figure 3.20. The mean correlations were -.75 and -.81 respectively.

Figure 3.18 Scatterplot of accuracy and time-to-hit by condition of latency from participant # 101. The constant latency condition is referred to as “Baseline Latency” in this plot.
**Mean Pearson's r values.** A boxplot of the mean Pearson's r values from all 29 participants in the constant latency condition the correlations between sickness and accuracy, sickness and time-to-hit and accuracy and time-to-hit are provided in Figure 3.19 below.

![Boxplot of Pearson's r values](image)

*Figure 3.19 Boxplot of Pearson's r values averaged across the 29 participants showing the range of the data points for the within-subjects correlation of accuracy and time-to-hit in the constant latency condition.*
A boxplot of the mean Pearson's $r$ values from all 29 participants in the constant latency condition the correlations between sickness and accuracy, sickness and time-to-hit and accuracy and time-to-hit are provided in Figure 3.20 below.

![Boxplot of Pearson's r values](image)

**Figure 3.20** Boxplot of Pearson's $r$ values averaged across the 29 participants showing the range of the data points for the within-subjects correlation of accuracy and time-to-hit in the varying latency condition.
CHAPTER IV

Discussion

The purpose of this study was to determine how varying latency in a head-mounted display affects human performance. More specifically, the study examined the effects of system latency on sickness, accuracy, and time needed to perform a task. Overall, the findings indicate that human performance declines in the presence of latency. However, the relative contributions of sickness vs. latency to the performance decrement remain unclear.

Withdrawal Rate

It was hypothesized that there would be a higher withdrawal rate in the varying latency condition compared to the constant latency condition. However, in the current study we had too few withdrawals to perform a statistical analysis. St. Pierre, et al. (2015) reported an overall study withdrawal rate of 9%, with a 23% withdrawal rate in the same varying latency condition used in this study. Kinsella (2014) reported a 20.8% (25/120) withdrawal rate in her study. In comparison, the withdrawal rate for the present study was 3%, with one withdrawal from each latency condition. The studies were the same in almost all criteria, including the screening questionnaire, prompts if a “severe” response was received and the ability for the participants to stop the trials if desired. One difference between the studies was that both Kinsella (2014) and St. Pierre, et al. (2015) provided a handrail for balance. The handrail was not used in the current study. The absence of the handrail did not affect the withdrawal rate; in fact, the withdrawal rate was lower in the current study without the additional kinesthetic reference provided by the
handrail. Although the experiments were equivalent, there were statistical differences in the levels of sickness between the current study and previous studies that are examined below.

**Hypotheses**

**Sickness.** It was hypothesized that there would be a main effect of condition on reported sickness scores. This hypothesis was not supported as no significant difference in condition was found. However, the trend was in the expected direction. Furthermore, current results failed to replicate previous research conducted using the object location task, specifically previous studies found that varying amplitude of latency resulted in greater sickness reports compared to constant latency (Kinsella, 2014; Moss et al., 2011; St. Pierre et al., 2015), but the current study did not. To examine possible reasons for the differences in findings, sickness levels obtained by St. Pierre, et al., (2015) and the current study from the same latency conditions were compared.

*Table 4.1 Statistical summary for St. Pierre, et al. (2015) and the current study showing the sickness levels (SQRT(Peak SSQ) for constant and varying latency conditions.*

<table>
<thead>
<tr>
<th>Condition</th>
<th>Constant Latency</th>
<th>Varying Latency</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>N</td>
</tr>
<tr>
<td>St. Pierre, et al.</td>
<td>4.14</td>
<td>2.84</td>
<td>30</td>
</tr>
<tr>
<td>Current Study</td>
<td>5.89</td>
<td>3.27</td>
<td>29</td>
</tr>
<tr>
<td><em>t</em>-tests</td>
<td><em>t</em> (57) = 2.20, <em>p</em> = .03 (1-tailed)</td>
<td><em>t</em> (57) = 1.69, <em>p</em> = .09 (1-tailed)</td>
<td></td>
</tr>
</tbody>
</table>
As can be seen in Table 4.1 above, in the constant latency condition there is a significantly higher sickness level in the current study than in the study by St. Pierre, et al., (2015). Although the object location task was the same as used by Kinsella (2014), Moss and Muth (2011) and St. Pierre, et al., (2015), one notable difference was that participants in the previous studies used a handrail for balance. The handrail served as a fixed reference point that provided kinesthetic information and tactile cueing which should have led to reduced sickness levels in the study by St. Pierre, et al., (2015) compared to the current study where the handrail was absent. Further, the absence of the handrail allowed for an increase in the amount of torso rotation in the current study, related to the need to rotate the shoulders more in order to aim the laser pointer at the targets. Torso rotation has been shown to provoke motion sickness symptoms and it has been used as a stimulus to provoke motion sickness symptoms in some studies (Bouyer & Watt, 1996a, 1996b; Cloutier & Watt, 2007). In fact, there was a measurable amount of sickness after the training session and before the experimental session even began. This was not the case in previous studies that had much shorter training periods with the handrail. This effect of training on sickness may account for the slight increase in sickness scores in the constant condition. In the varying latency condition, sickness scores were lower than scores found by St. Pierre, et al. (2015) however not at a statistically significant level. This difference may be due to the increased amount of concentration required during the targeting task, as it was more difficult to score a hit in the varying latency condition than in the constant condition. This supports previous
research showing that mental engagement in a task may lower sickness levels (Bos, 2015; Matsangas, McCauley, & Becker, 2014).

Sickness levels increased significantly over time in both conditions. Participants began the study with minimal symptoms, progressing to problematic levels by the end of the blocks of trials. This confirms previous research conducted using this paradigm showing that sickness levels increase over time with exposure to latency in HMDs (Kinsella, 2014; Moss et al., 2011; St. Pierre et al., 2015).

**Accuracy.** It was hypothesized that there would be a main effect of condition on accuracy. This hypothesis was supported as participants were less accurate (scored significantly fewer hits) in the varying latency condition than in the constant latency condition. Participants averaged 33.8 hits per block of 40 trials or 84.5% accuracy during the constant latency condition compared to an average of 23.8 hits per block of 40 trials or 59.5% accuracy during the varying latency condition. This confirms the hypothesis that accuracy varies by condition, with better accuracy in the constant latency condition than in the varying latency condition and clearly demonstrates how latency affects performance. Studies of vehicle simulators have noted that latency not only causes sickness, but often can degrade performance as well (Frank, Casali, & Wierwille, 1988).

Accuracy was hypothesized to decrease for each block of trials due to increasing sickness levels as the task progressed. However, the data showed a trend in the opposite direction, showing an increase in accuracy over time. When this study was conceived, it was thought that the levels of sickness would cause greater amounts of disruption in the targeting task over time, resulting in gradually decreasing numbers of hits. While
sickness did indeed increase overtime, performance improved over time. Nonetheless, the performance improvement was more pronounced in the constant latency condition than in the varying latency condition (see Figure 3.4). This may be evidence that varying latency interferes with performance improvement over time. This effect should be further investigated in future studies.

**Time-to-hit.** It was hypothesized that there would be a main effect of condition on the time needed to hit a target, with more time-to-hit needed for targets in the varying latency condition than in the constant latency condition. This hypothesis was supported, as participants required an average of 21.44 seconds longer to complete a block of trials in the varying latency than the constant latency condition. Participants averaged 84.1 seconds to complete a block of trials, or 2.1 seconds per trial in the varying condition compared to 59.5 seconds to complete a block of 40 trials, or 1.5 seconds per trial in the constant condition. Latency was 70 ms in the constant condition and averaged 170 ms in the varying condition, resulting in a net difference of approximately 100 ms between the two conditions. After adjusting the time-to-hit values to account for the 100 ms difference in latency, there is still a 0.5 second difference between the times-to-hit in the constant latency and varying latency conditions (1.5 seconds-base, 2.0 seconds-varying). This implies that the performance difference is not simply due to the presence of the latency and may be associated with other factors such as sickness. Nonetheless, the majority of the difference appears to be due to the direct effect of varying latency on performance. This may be due to the unstable sensory rearrangement created by the varying latency condition, which limited the ability for the participants to adapt their behavior to the
latency in order to improve their performance over time. Further, the latency created a significant delay in the visual feedback that the participants used to adjust their point-of-aim while performing the targeting task. Delayed visual feedback has been found to increase the complexity of tasks where timing is critical to performance such as lane keeping or obstacle avoidance tasks (Morice et al., 2008).

The average time necessary to complete a block of trials decreased over time, opposite of the hypothesized effect. It was thought that the levels of sickness over time would interfere with performance such that greater times would be needed for each block of trials. As discussed above, the effects of sickness over time were impacted by the engagement in novel tasks and limited the effects of sickness on the time needed to hit a target (Bos, 2015) and there may be a training effect of performing the targeting task in a HMD.

**Relationship Between Sickness and Performance**

**Overall Relationships.** When the relationships between sickness, accuracy, and time-to-hit were examined, the data showed that, as sickness increased, the number of hits decreased, with sickness accounting for 9.4% of the variance in the number of hits. As sickness increased, the time needed for hits increased, with sickness accounting for 12.4% of the difference in cumulative times. As the number of hits decreased, the time-to-hit increased significantly, with time-to-hit accounting for 88.5% of the variance in the number of hits. This would indicate that when the data are examined at the between-subjects level, sickness adversely effects performance. The relationship between the number of hits and time-to-hit is extremely strong, indicating that these two performance
measures might be evaluating the similar performance relationships. The strength of this relationship raised concerns that the measures may be too similar to be considered independent. Additional analysis of hits and time-to-hit using an alternative strategy is provided in Appendix O.

**Within Condition Relationships.** The relationships between sickness, and accuracy within the constant latency condition showed slightly stronger relationships than in the varying latency condition. In the constant condition, as sickness increased, the number of hits decreased, with sickness accounting for 14.6% of the variance in the number of hits. As sickness increased, the time-to-hit increased, with sickness accounting for 17.5% of the variance in time-to-hit. In the varying latency condition, as sickness increased, the number of hits decreased, with sickness accounting for 10.8% of the variance in the number of hits. As sickness increased, the time-to-hit increased, with sickness accounting for 17.9% of the variance in cumulative times. In both conditions, as the number of hits decreased, the time-to-hit increased significantly, with time-to-hit accounting for 76.4% of the variance in the number of hits in the constant condition and 88.6% of variance in the varying latency condition. These results are similar to those above and indicate that sickness adversely effects performance in each condition. Additionally, the relationship between hits and time-to-hit remained extremely strong in each condition supporting the need to investigate this relationship further.

**Within-Subjects Correlations.** Finally, the relationships between sickness, accuracy, and time-to-hit were examined at the individual level. As sickness increased, the number of hits decreased for a majority of the participants. As sickness increased, the
time-to-hit increased for a majority of the participants. When the average within-subjects correlations were examined, the mean overall Pearson’s $r$ values for sickness and accuracy were almost zero, yielding $r$-squared values near zero. For sickness and time-to-hit the overall Pearson’s $r$ values were low, with sickness explaining 4% of the variance in time-to-hit. Further examination of these correlations within each latency condition resulted in similar results. In the constant latency condition, sickness explains 4% of the variance in accuracy and 5.8% of the variance in time-to-hit. Whereas in the varying latency condition, sickness accounts for almost none of the variance in accuracy and only 2.9% of the variance in time-to-hit. These analyses highlight the fact that during this study, performance was highly variable at the individual level, making it difficult to determine the role of sickness in performance. As above, hits and time-to-hit remained highly correlated when examined at the individual level providing further evidence of the need for a more in-depth analysis.

**Differences in Human Performance Due to Delayed Feedback**

The constant latency condition simulated a non-head tracked virtual environment with a constant latency of 70 ms of fixed latency. Therefore, when individuals moved their heads, the display showed corresponding movement in the same direction at an almost imperceptible level. During the targeting task, participants were able to see where their laser pulses were hitting in near real time, and received almost immediate (stable) feedback to use to adjust their aim point and score a hit.

In contrast, the varying latency condition simulated a head-tracked HMD with a total latency of 70-270 ms varying at a 0.2 Hz frequency (St. Pierre et al., 2015) or an
average total latency of 170 ms of latency. Therefore, when individuals moved their heads (and torsos), the display lagged behind their movement in randomly varying amounts, ranging from barely noticeable to extremely noticeable levels. This resulted in delayed or unstable feedback that was not as useful in adjusting the aiming-point of the laser pointer.

Wickens and Hollands discuss how time delays are harmful to tasks requiring real-time tracking and feedback for proper performance stating that "Pure time delays are universally harmful in tracking, and tracking performance gets progressively worse with greater delays" (Wickens & Hollands, 2000, pp 398-401). The time delay experienced in the varying latency condition may offer additional proof that head-tracked HMD systems may not offer stable feedback necessary for targeting applications.

This study provides additional support to the effects of delayed feedback and how delayed feedback adversely affects human performance. These effects are observable in the analysis of the accuracy data in this study (see Figure 3.4). In the constant latency condition, participants were more accurate over time, with gradually increasing scores and small, consistent standard error amounts. In contrast, during the varying latency condition, participants were less accurate and their performance was highly variable over time, showing a sinusoidal pattern of hits over time with larger standard errors.

**Sensory Rearrangement and Implications for Adaptation**

In the current study, individuals in the varying latency condition performed worse (scored fewer hits, took longer for hits) than those in the constant condition. Similar results were found in studies using constant and varying prismatic displacement. While
performing a target pointing task, subjects exposed to variable displacement (unstable feedback) performed worse, that is had larger errors than subjects exposed to constant displacement (stable feedback) conditions (Cohen & Held, 1960; R. Welch & Cohen, 1991). Welch states that "An inter- or intrasensory discordance must be stable in some sense, if adaptation is to occur" (R. B. Welch, 1978, p.17). The perceptual modifications resulting from exposure to varying latency can be interpreted as exposure to an unstable stimulus, thereby preventing or interfering with the ability of humans to adapt to it.

Welch defined adaptation to perceptual rearrangement as "a semi-permanent change of perception or perceptual-motor coordination that serves to reduce or eliminate a registered discrepancy between or within sensory modalities or the errors in behavior induced by the discrepancy" (R. B. Welch, 1978, p.8). His definition highlights the importance of this research, to reduce or eliminate errors in behavior caused by perceptual modifications. We need to proceed carefully when deploying new visual technologies to ensure that they operate within the limitations and capabilities of the human using them and do not create discrepancies between human sensory modalities or cause errors in behavior.

For example, night vision devices have been successfully integrated into most aerial platforms requiring precise navigation and other low-level flight operations, even on the darkest of nights. These systems are designed such that they have no noticeable latency during operations. As technologies improved, attempts were made to incorporate new head-tracked HMD displays and technologies into modern aircraft to increase situational awareness. Some of these newer systems have caused performance errors
similar to those caused by system latencies in this study. The original helmet designed for use with the Lockheed F-35 Joint Strike Fighter is an example of technological advancement being in conflict with human limitations. The helmet system collects information from the plane’s sensors and fuses it with imagery from six cameras mounted on the outer surfaces of the aircraft. This system provides the pilot with a 360-degree view, augmented with sensor information, that is projected directly onto their visor. Reported system latencies for the F-35’s flight symbology is relatively low (about 50 ms), however latency for the visual system which displays blended information from cameras and sensors has been reported at 133 ms or more. There is no published research on the variability of system latency in this system (Carey, 2012). A recent study measured pilot performance on complex tasks while using an upgraded version of the HMD system described above, finding that performance was significantly degraded with latencies above 100 ms (Jenkins & Havig, 2015).

**Study Limitations and Future Research**

This study was strengthened by its within-subjects design. Even so, differences in motion sickness symptoms based on age and ethnicity have been reported (Golding, 2006). Study participants ranged in age from 18-26 and were mostly Caucasian, limiting the generalizability of these findings. Nonetheless, a wide distribution of sickness scores was observed, with high levels of individual differences observed in the within-subject correlational analysis between sickness and performance, suggesting that motion sickness susceptibility was adequately sampled.
In future research examining the effects of sickness on performance, a screening tool such as the MSSQ-S (Golding, 2006) could be incorporated in an effort to exclude subjects who have low or no susceptibility to motion sickness. This may limit the statistical influence observed when including non-symptomatic individuals.

The effects of training (learning the locations of the targets and how to use the laser pointer to score a hit) were controlled for by having the participants perform the targeting task prior to exposure to the HMD stimulus. However, participants were not trained on how to perform the task while wearing the HMD resulting in an observed increase in performance over time when performing the task in the HMD.

The amount of time between experimental sessions was deliberately chosen to prevent any effects of habituation or adaptation to the stimulus in order to isolate the conditions. Future efforts should examine the effects of motion sickness adaptation to the latency conditions used in this experiment by scheduling experimental sessions closer together, optimally less than 4, but not more than 7 days apart (Lawson, 2014).

During this experiment, we relied on the HMD to induce sickness. It may be beneficial to induce mild motion sickness or soporific symptoms prior to exposure to the targeting task in order to examine how performance is affected by sickness. Additionally, the amount of time spent in the stimulus was limited to about 15 minutes, with 1-minute interruptions for the SSQ for every 2-minutes of trials. Future research should consider a simpler verbal probe such as a Subjective Units of Distress Scale (Hodges, Kooper, & Meyer, 1995; Maltby & Kirsch, 2002) between blocks of trials and reserve the SSQ for
the end point sickness assessment, resulting in a more continuous stimulus and longer exposures during the experimental session.

The next study. The next study conducted should repeat the current study with three modifications. One, in an effort to reduce the adverse statistical effects of individuals that do not experience sickness symptoms, use the MSSQ-S score to screen participants, limiting the study to those with a MSSQ-S score above zero. Two, since training effects in the current study occurred when the subjects first donned the HMD, recommend the following changes: omit the training with no HMD and reduce the number of blocks of training trials. The revised training period should consist of 3 blocks of training trials in the HMD with constant latency condition, as pilot testing indicated that beginning in the 3rd block of trials, the mean number of hits stayed above 38 for the remaining 27 blocks of trials. Three, during the experimental sessions, select latency values that are the similar: constant latency with base plus 100 ms (170 ms constant latency); and varying latency of base plus 100 ms, +/- 20-100 ms of latency varying at 0.2 Hz (average of 170 ms varying latency). The remainder of the study should be kept the same as the current study. These changes would eliminate the majority of the shortcomings in the present study by eliminating the adverse statistical effects of asymptomatic individuals, eliminating the training effects in the HMD and limiting the time differences in the latency manipulations The revised study should highlight any performance differences between the latency conditions.
Conclusion

This study demonstrated that human performance is negatively impacted by the presence of latency. The current study when contrasted with our previous work (Kinsella, 2014; St. Pierre et al., 2015), also seemed to indicate that sickness levels can be reduced by introducing a novel and challenging task. However, it is unclear if the performance decrements associated with the different latency conditions were due mostly to the latency itself, or at least partially due to another underlying causal influence such as motion sickness. This study also was not able to determine if there was an effect of the sickness induced by the latency on performance, despite that fact, sickness and performance did appear to correlate. Future work should try to tease apart the effects of latency and sickness on performance.

The use of HMDs will increase in the future, with designers incorporating them into technology in new and modern ways. This will cause the exposure of larger populations to stimuli that have proven to induce sickness and affect performance. Greater understanding of the possible effects of interacting with a virtual world, or controlling a vehicle via a head-tracked remote camera are necessary in order to successfully incorporate these technologies into our lives. This study offers insight to the importance of how performance in a head-tracked HMD may be affected if the effects of varying latency are not eliminated or controlled.
Appendix A
IRB Approved Consent Form

Information about Being in a Research Study
Clemson University

Effects of Helmet-Mounted Display Characteristics on User Experience

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

Your part in the study will be to

1. Have the distance between your 2 eyes measured.

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

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

4. “Shoot” at targets around the room with a laser pointer.

5. Complete several questionnaires asking you questions about your personal health history and motion sickness experiences.

There will be approximately 200 participants in this study. It will take you approximately 1 hour and 45 minutes to complete this study. You may be asked to return to complete this study multiple times if you are willing.

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

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

However, this study may lead to a better understanding of which characteristics of HMDs make them more user friendly. There are very few published studies examining design characteristics of HMDs. Studying these characteristics will lead to better HMD design for both military and civilian applications.

Incentives
By participating in this study, you will receive a monetary payment of $15 for the first session you participate in and an additional $35 if you participate in a second session. You may also receive course extra credit from participating. Note, the same course/extra credit is available for a no research activity.

Last updated 12/16/15
This form is valid only if the Clemson University IRB stamp of approval is shown here:
that involves the same effort and time investment (see your course instructor for more information on credit alternatives).

**Protection of Privacy and Confidentiality**
We will do everything we can to protect your privacy and confidentiality. We will not tell anybody outside of the research team that you were in this study or what information we collected about you in particular. Your name and the information collected from you for the study will be kept in separate locked locations such that your name and the information that is collected from you are not linked in an easy manner. Your identity will not be revealed in any publication that might result from this study or shared without your permission.

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

**Choosing to Be in the Study**
You do not have to be in this study. You may choose not to take part and you may choose to stop taking part at any time. You will not be punished in any way if you decide not to be in the study or to stop taking part in the study. If you decide not to take part or to stop taking part in this study, it will not affect your grade in any way.

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

**Contact Information**
If you have any questions or concerns about this study or if any problems arise, please contact Dr. Eric R. Muth at Clemson University at 864-656-6741. If you have any questions or concerns about your rights in this research study, please contact the Clemson University Office of Research Compliance (ORC) at 864-656-0636 or irb@clemson.edu. If you are outside of the Upstate South Carolina area, please use the ORC’s toll-free number, 866-297-3071.

**Consent**

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

Participant’s signature: ___________________________ Date: ______________

A copy of this form will be given to you.
## Screening Questionnaire

Subject Number: __________________________ Date: __________________________

<table>
<thead>
<tr>
<th>Questions</th>
<th>Answers</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any stomach problems?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Any heart problems?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Any brain problems?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Any visual problems (other than glasses)?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Do you have any inner ear problems?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Do you smoke?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>If female, are you pregnant?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Currently taking any medications?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Do you have any experience with helmet-mounted displays?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Do you have any experience with virtual reality simulators/environments?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Do you have vertigo?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Do you easily get motion sick?</td>
<td>Y / N</td>
<td></td>
</tr>
<tr>
<td>Gender:</td>
<td>M / F</td>
<td></td>
</tr>
<tr>
<td>Ethnicity:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Which is your dominant hand?</td>
<td>L / R</td>
<td></td>
</tr>
<tr>
<td>When was the last time you ate?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Instructions for participants:**
1. No vigorous exercise for at least 1 hour before the experiment.
2. No smoking or using any tobacco product, drinking alcohol, or drinking caffeine for at least 8 hours before the experiment.
### Appendix C

#### MSSQ-S

**Motion sickness susceptibility questionnaire short-form (MSSQ-Short)**

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your childhood experience only (before 12 years of age), for each of the following types of transport or entertainment please indicate

1. As a child (before age 12), how often you felt sick or nauseated (tick boxes)

<table>
<thead>
<tr>
<th></th>
<th>Not Applicable - Never Traveled</th>
<th>Never Felt Sick</th>
<th>Rarely Felt Sick</th>
<th>Sometimes Felt Sick</th>
<th>Frequently Felt Sick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Buses or Coaches</td>
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<tr>
<td>Trains</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Small Boats</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ships, e.g. Channel Ferries</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swings in playgrounds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roundabouts in playgrounds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Dippers, Funfair Rides</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Your experience over the last 10 years (approximately), for each of the following types of transport or entertainment please indicate

2. Over the last 10 years, how often you felt sick or nauseated (tick boxes)

<table>
<thead>
<tr>
<th></th>
<th>Not Applicable - Never Traveled</th>
<th>Never Felt Sick</th>
<th>Rarely Felt Sick</th>
<th>Sometimes Felt Sick</th>
<th>Frequently Felt Sick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buses or Coaches</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trains</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Boats</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ships, e.g. Channel Ferries</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swings in playgrounds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roundabouts in playgrounds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Dippers, Funfair Rides</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Score to give the MSSQ-Short raw score (possible range from minimum 0 to maximum 54). MSSQ raw score $= MSA + MSB$. 

73
INTRODUCTION:
This questionnaire is designed to determine:
(a) how susceptible to motion sickness you are, and
(b) what sorts of motion are most effective in causing that sickness

QUESTIONNAIRE:

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

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

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

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

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

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

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

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

   Cars_____  Ships_____
   Buses_____  Swings_____
   Trains_____  Amusement
   Airplanes_____  Rides_____
   Small Boats_____  Others (specify)
Simulator Sickness Questionnaire (SSQ)

Subject Number:  
Date:  
Session:  

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

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>General discomfort (N,O)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>2.</td>
<td>Fatigue (O)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>3.</td>
<td>Headache (O)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>4.</td>
<td>Eyestrain (O)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>5.</td>
<td>Difficulty focusing (O,D)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>6.</td>
<td>Increased salivation (N)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>7.</td>
<td>Sweating (N)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>8.</td>
<td>Nausea (N)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>9.</td>
<td>Difficulty concentrating (N,O)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>10.</td>
<td>Fullness of head (D)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>11.</td>
<td>Blurred vision (O,D)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>12.</td>
<td>Dizzy (eyes open) (D)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>13.</td>
<td>Dizzy (eyes closed) (D)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>14.</td>
<td>Vertigo (D)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>15.</td>
<td>Stomach awareness (N)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>16.</td>
<td>Burping (N)</td>
<td>None</td>
<td>Slight</td>
<td>Moderate</td>
</tr>
<tr>
<td>Symptom</td>
<td>PRE</td>
<td>POST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>-----</td>
<td>------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt sick to my stomach</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt faint-like</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt annoyed/irritated</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt sweaty</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt queasy</td>
<td>5</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt lightheaded</td>
<td>6</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt drowsy</td>
<td>7</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt clammy/cold sweat</td>
<td>8</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt disoriented</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt tired/fatigued</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt nauseated</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt hot/warm</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt dizzy</td>
<td>5</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt like I was spinning</td>
<td>6</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt as if I may vomit</td>
<td>7</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I felt uneasy</td>
<td>8</td>
<td>9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Appendix G

### List of Targets

<table>
<thead>
<tr>
<th>Block # 1</th>
<th>Block # 2</th>
<th>Block # 3</th>
<th>Block # 4</th>
<th>Block # 5</th>
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<tbody>
<tr>
<td>Left Clock</td>
<td>Right Shelf</td>
<td>Right Fire</td>
<td>Right Fan</td>
<td>Left Flag</td>
</tr>
<tr>
<td>Right Cross</td>
<td>Left Scale</td>
<td>Left Scale</td>
<td>Left Flag</td>
<td>Right Cross</td>
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<td>Right Flag</td>
<td>Right Cross</td>
<td>Right Fan</td>
<td>Left Hall</td>
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<td>Left Hall</td>
<td>Right Hall</td>
<td>Left Flag</td>
<td>Left Clock</td>
<td>Right Shelf</td>
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<tr>
<td>Right Fan</td>
<td>Right Cross</td>
<td>Right Cross</td>
<td>Left Fire</td>
<td>Left Hall</td>
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<tr>
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<td>Right Fan</td>
<td>Left Clock</td>
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<td>Right Shelf</td>
<td>Left Scale</td>
<td>Right Fire</td>
<td>Right Cross</td>
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**Total Misses**

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**Total Misses**
Summary of Appendix H: a simple linear regression was calculated to predict sickness (SQRT(PeakSSQ)) based on MSHQ (SQRT(MSHQ)). A significant regression equation was found ($F(1,56) = 9.51$, $p < .01$), with an $R^2$ of .15. Participants' predicted sickness score (SQRT(PeakSSQ)) is equal to 4.17 + .63 (SQRT(MSHQ)) units.

NOTE: The MSHQ was not analyzed in the main document. The following analysis is included for future reference.

Participants completed the Motion Sickness History Questionnaire (MSHQ) during their first experimental session. The MSHQ scores for the 29 participants ranged from 0 to 54 ($M = 13.5$, $SD = 13.1$) and was not normally distributed based on the Shapiro-Wilks normality test, $W(29) = 0.87$, $p < .01$. The positively skewed distribution is shown in Figure H.1 below.

![Histogram of MSHQ data showing non-normal distribution of scores.](image)

Figure H.1 Histogram of MSHQ data showing non-normal distribution of scores.
Further analysis determined that the MSHQ data for participant number 122 was an outlier as its value was beyond 1.5 times the interquartile range above the 3rd quartile as shown in the boxplot of the MSHQ data in Figure H.2.

![Boxplot of MSHQ data showing participant 122 as an outlier.](image)

**Figure H.2 Boxplot of MSHQ data showing participant 122 as an outlier.**

A square-root transformation was performed on the MSHQ data to correct for positive skewness (Bland & Altman, 1996), resulting in a normal distribution with no outliers as can be seen in Figure H.3 below.
Next, a simple linear regression was calculated to predict sickness (SQRT(PeakSSQ)) based on MSHQ (SQRT(MSHQ)). A significant regression equation was found ($F(1, 56) = 9.51, p < .01$), with an $R^2$ of .15. Participants' predicted sickness score (SQRT(PeakSSQ)) is equal to $4.17 + .63$ (SQRT(MSHQ)) units.

![Histogram showing the normal distribution of the MSHQ scores after performing the square-root transformation.](image_url)

**Figure H.3** Histogram showing the normal distribution of the MSHQ scores after performing the square-root transformation.
Summary of Appendix I: The analysis of the data with the zero participants removed did not change any of the findings of the main document. There were small changes in the values of the statistical tests.

Analysis of Sickness and Performance with Non-Symptomatic Participants Removed

During data analysis it was observed that three participants had reported no sickness symptoms (SSQ=0) for all blocks of trials in both latency conditions. The analysis of sickness, accuracy and time-to-hit were repeated after removing three participants to determine if their inclusion in the analyses effected the overall outcome of the experiment.

The Effects of Latency on Sickness

The effects of added frequency and amplitude of latency on peak SSQ scores was first assessed with a 2 (HMD condition) X 6 (block) Repeated Measures ANOVA. A significant effect of block was found, $F(5,44) = 18.08, p < .01, \eta_p^2 = .67$. There was no significant effect of condition, $F(1,48) = 0.19, p = .66, \eta_p^2 = .00$ and no evidence supporting an interaction between condition and block $F(1,48) = 0.05, p = .82, \eta_p^2 = .00$. A graph of SSQ by condition is shown in Figure I.1 below.

To further examine the effects of condition on sickness, a paired-samples $t$-test (directional according to the hypotheses) was conducted using peak SSQ scores between the base ($M = 6.51, SD = 2.86$) and varying latency ($M = 7.04, SD = 2.83$) conditions. This analysis found a significant difference between the peak sickness levels between base and varying latency conditions, $t (26) = -1.95, p = .03$ (1-tailed), $d = .19$. 

81
Figure I.1 Sickness scores (square root of SSQ) shown per block of trials showing that sickness increases over block of time and varies by condition. Constant latency is labeled “Baseline Latency” in the graph above.

Analysis of Covariates

(Note: This analysis for the main study appears in Appendix N. It is included in this section to keep the two separate while examining the effects of removing participants with zero SSQ scores.)

Several factors were examined for their effect on sickness levels. Anxiety levels during the exposure to the stimuli were measured by the State-Trait Anxiety Inventory
(State) and motion sickness susceptibility as measured by the MSSQ-S were both significantly correlated with peak sickness scores. As a result, they were analyzed as covariates with a 2 (condition) X 6 (block) Repeated Measures ANCOVA. The ANCOVA [between-subjects factor: condition (base and varying latency); covariate: anxiety (STAI-State), and covariate: motion sickness susceptibility (MSSQ-S)] revealed no main effects of condition, \( F(1,52) = .00, p = .98, \eta^2_p = .00 \), a significant effect of anxiety, \( F(1,52) = 27.82, p < .01, \eta^2_p = .35 \), and a significant effect of motion sickness susceptibility, \( F(1,52) = 6.45, p = .01, \eta^2_p = .11 \). A graph of sickness by condition while controlling for anxiety and susceptibility is shown in Figure I.2 below.

![Sickness scores (square root of SSQ) shown per block of trials after controlling for anxiety and motion sickness susceptibility showing that sickness increases over block of time and does not vary by condition. The constant latency condition is labeled as “Baseline Latency” in this graph.](image)

Figure I.2 Sickness scores (square root of SSQ) shown per block of trials after controlling for anxiety and motion sickness susceptibility showing that sickness increases over block of time and does not vary by condition. The constant latency condition is labeled as “Baseline Latency” in this graph.
The Effects of Latency on Performance

The effects of added amplitude and frequency of latency on performance were analyzed by examining two performance measures, accuracy and time-to-hit. As with the SSQ data, the distributions of both accuracy and time-to-hit were examined across the blocks and were found to be normally distributed with equal variances.

**Accuracy.** A 2 (HMD condition) X 5 (block) repeated measures ANOVA examined the effects on accuracy. Accuracy results by condition and block are shown in Figure I.3 below. As can be seen in Figure I.3 below, a significant effect of condition was found, $F(1,48) = 37.84, p < .01, \eta^2_p = .44$ with lower accuracy in the varying latency condition compared to the constant latency condition. A significant effect of block was also found in which accuracy increased over each block, $F(4,45) = 11.17, p < .01, \eta^2_p = .50$. There was no support for an interaction between condition and block $F(4,48) = 1.59, p = .18, \eta^2_p = .03$. 
Figure I.3. The performance measurement "accuracy" showing an increase in number of hits over time and differences between latency conditions. The constant latency condition is labeled “Baseline Latency” in this graph.
**Time-to-hit.** Time-to-hit was derived by summing the times for each trial within each block of 40 trials. The mean time for each block was converted to a rate (seconds per hit) by dividing the mean block time by 40 (total trials). A 2 (HMD condition) X 5 (block) repeated measures ANOVA examined the effects on time-to-hit. As shown in Figure I.4 below, a significant effect of condition was found, $F(1,47) = 53.20, p < .01, \eta_p^2 = .53$, with slower time-to-hit in the varying latency condition compared to the constant latency condition. A significant effect of block was also found such that the time-to-hit the target improved across blocks, $F(4,44) = 30.6, p < .01, \eta_p^2 = .74$. There was no support for an interaction between condition and block, $F(4,44) = 0.76, p = .56, \eta_p^2 = .06$.

![TIME-TO-HIT (N=25, zero SSQ Removed)](image)

*Figure I.4 Graph of the performance measurement "time-to-hit" showing mean seconds per hit per block of trials for each latency condition. The constant latency condition is labeled “Baseline Latency” in this graph.*
Correlational Analyses

**Overall.** A series of Pearson product-moment correlation coefficients were computed to assess the relationship between the peak sickness levels, accuracy and time-to-hit. The number of hits were negatively correlated with sickness, $r = -.31$, $n = 58$, $p = .010$, indicating that as sickness increases, accuracy decreases. Time-to-hit was positively correlated with sickness, $r = .35$, $n = 58$, $p < .01$, indicating that as that as sickness increases, the time-to-hit increases. There was a strong negative correlation between time-to-hit and accuracy, $r = -.94$, $n = 58$, $p < .01$, indicating that as accuracy decreases the time-to-hit increases.
Summary of Appendix J: Significant regression equations were found for sickness, accuracy and time-to-hit.

Performance Analysis with Regression

Sickness. Data analysis indicated that sickness levels, motion sickness susceptibility and anxiety level at the end of the experimental trials were significantly correlated. A simple linear regression equation was calculated to predict the participant's sickness level based on their motion sickness susceptibility percentile approximation and their anxiety level at the end of the experimental trials. A significant regression equation was found, $F(2,55) = 35.9, p < .01, R^2 = .57$. The participant's sickness score (SQRT(Peak SSQ)) is equal to $-.55 + 0.28$ (MSSQ-S Percentile Score) + 0.14 (STAI-State).

When we control motion sickness susceptibility on the relationship between sickness levels and anxiety at the end of the experimental trials, we find the following partial correlation, $r = .27, p = .04$. When we control anxiety at the end of the experimental trials on the relationship between sickness levels and motion sickness susceptibility, we find the following partial correlation, $r = .65, p < .01$. 
**Accuracy.** Data analysis showed that the number of hits, latency condition and gender were significantly correlated. A simple linear regression equation was calculated to predict the participant's number of hits based on the latency condition and gender. A significant regression equation was found, $F (2,55) = 19.50, p < .01, R^2 = .41$. The participant's number of hits are equal to $61.67 - 9.97$ (Condition 3 = Constant Latency, 4 = Varying latency) + 3.85 (gender, 0 = female, 1 = male).

When we control condition of latency on the relationship between accuracy and gender, we find the following partial correlation, $r = -0.62, p < .01$. When we control gender on the relationship between accuracy and condition of latency, we find the following partial correlation, $r = 0.29, p = .03$.

**Time-to-Hit.** Data analysis showed that the time-to-hit, latency condition, gender and anxiety level at the end of the experimental trials were significantly correlated. A simple linear regression equation was calculated to predict the participant's time-to-hit based on the latency condition, gender and their anxiety level at the end of the experimental trials. A significant regression equation was found, $F (3,54) = 25.9, p < .01, R^2 = .59$. The participant's time-to-hit is equal to $-4.9 + 0.60$ (Condition 3=Constant Latency, 4=Varying latency)) - 3.85 (gender, 0 = female, 1 = male) + .01(MSSQ-S Percentile Score).

When we control condition of latency on the relationship between time-to-hit, gender and anxiety level at the end of the experimental trials, we find the following partial correlation, $r = 0.72, p < .01$. When we control gender on the relationship between time-to-hit, condition of latency and anxiety level at the end of the experimental trials we
find the following partial correlation, $r = -0.40, p < .01$. When we control anxiety level at the end of the experimental trials on the relationship between time-to-hit, condition of latency and gender, we find the following partial correlation, $r = .34, p = .01$. 
Appendix K
Within-Subjects Correlations Individual Graphs
SICKNESS and ACCURACY by Condition of Latency

Note: The constant latency condition is referred to as “Baseline Latency” in the following graphs.
Individual Subjects Correlations
SICKNESS and ACCURACY
By Latency Condition

Participant # : 105

Condition
- Baseline Latency
- Variable Latency

Number of Hits
SQRTPeak SSQ

Individual Subjects Correlations
SICKNESS and ACCURACY
By Latency Condition

Participant # : 106

Condition
- Baseline Latency
- Variable Latency

Number of Hits
SQRTPeak SSQ
Individual Subjects Correlations
SICKNESS and ACCURACY
By Latency Condition

Participant # : 109

Condition
- Baseline Latency
- Variable Latency
- Baseline Latency
- Variable Latency

Baseline Latency : R2
Linear = 0.313
Variable Latency : R2
Linear = 0.295

Sqrt(Peak SSQ)

Number of Hits

Individual Subjects Correlations
SICKNESS and ACCURACY
By Latency Condition

Participant # : 110

Condition
- Baseline Latency
- Variable Latency
- Baseline Latency
- Variable Latency

Baseline Latency : R2
Linear = 0.084
Variable Latency : R2
Linear = 0.229

Sqrt(Peak SSQ)

Number of Hits
Individual Subjects Correlations
SICKNESS and ACCURACY
By Latency Condition

Participant # : 111

Condition
- Baseline Latency
- Variable Latency

SRT(Peak SSQ)

Number of Hits

Individual Subjects Correlations
SICKNESS and ACCURACY
By Latency Condition

Participant # : 112

Condition
- Baseline Latency
- Variable Latency

Baseline Latency : R^2
Linear = 0.665
Variable Latency : R^2
Linear = 0.280

SRT(Peak SSQ)

Number of Hits
Individual Subjects Correlations
SICKNESS and ACCURACY
By Latency Condition

Participant # : 123

Condition
- BaselineLatency
- Variable Latency
- BaselineLatency
- Variable Latency

BaselineLatency : R2
Linear = 0.006
Variable Latency : R2
Linear = 0.003

Number of Hits
SQR(T(Peak SSQ))

Individual Subjects Correlations
SICKNESS and ACCURACY
By Latency Condition

Participant # : 124

Condition
- BaselineLatency
- Variable Latency
- BaselineLatency
- Variable Latency

BaselineLatency : R2
Linear = 0.880
Variable Latency : R2
Linear = 0.298

Number of Hits
SQR(T(Peak SSQ))

102
Individual Subjects Correlations
SICKNESS and ACCURACY
By Latency Condition

Participant #: 130

Condition
- Baseline Latency
- Variable Latency

Baseline Latency: R² = 0.098
Variable Latency: R² = 0.142

SQRT(Peak SSQ) vs. Number of Hits
Note: The constant latency condition is referred to as “Baseline Latency” in the following graphs.
Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant #: 107

Condition
- Baseline Latency
- Variable Latency
 Baseline Latency: R2
 Linear = 0.659
 Variable Latency: R2
 Linear = 0.071

Seconds per Hit

SQRTPeak SSQ

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Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant #: 108

Condition
- Baseline Latency
- Variable Latency
 Baseline Latency: R2
 Linear = 0.209
 Variable Latency: R2
 Linear = 0.654

Seconds per Hit

SQRTPeak SSQ
Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant # : 109

Condition
- Baseline Latency
- Variable Latency

Baseline Latency : R^2
- Linear = 0.362
Variable Latency : R^2
- Linear = 0.347

Seconds per Hit

SQRTPeak SSQ

Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant # : 110

Condition
- Baseline Latency
- Variable Latency

Baseline Latency : R^2
- Linear = 0.222
Variable Latency : R^2
- Linear = 0.354

Seconds per Hit

SQRTPeak SSQ
Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant # : 117

SQURT(Peak SSQ)

Seconds per Hit

Condition

Baseline Latency
Variable Latency
Baseline Latency
Variable Latency
Baseline Latency : R^2
Linear = 0.576
Variable Latency : R^2
Linear = 0.093

Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant # : 118

SQURT(Peak SSQ)

Seconds per Hit

Condition

Baseline Latency
Variable Latency
Baseline Latency
Variable Latency
Baseline Latency : R^2
Linear = 0.028
Variable Latency : R^2
Linear = 0.757

114
Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant # : 121

Condition
- Baseline Latency
- Variable Latency

Seconds per Hit

Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant # : 122

Condition
- Baseline Latency
- Variable Latency

Baseline Latency: R2 Linear = 0.453
Variable Latency: R2 Linear = 0.006

Seconds per Hit
Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant # : 127

Seconds per Hit

Condition
- Baseline Latency
- Variable Latency

Baseline Latency : R^2
- Linear = 0.003
- Variable Latency : R^2
- Linear = 0.054

Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant # : 129

Seconds per Hit

Condition
- Baseline Latency
- Variable Latency

Baseline Latency : R^2
- Linear = 0.003
- Variable Latency : R^2
- Linear = 0.147
Individual Subjects Correlations
SICKNESS and TIME-TO-HIT
By Latency Condition

Participant #: 130

Condition
- Baseline Latency
- Variable Latency

Baseline Latency: R² = 0.003
Linear = 0.003
Variable Latency: R² = 0.054
Linear = 0.054
Note: The constant latency condition is referred to as “Baseline Latency” in the following graphs.
Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant # : 107

Condition
- BaselineLatency
- Variable Latency

BaselineLatency : R²
Linear = 0.424
Variable Latency : R²
Linear = 0.986

Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant # : 108

Condition
- BaselineLatency
- Variable Latency

BaselineLatency : R²
Linear = 0.811
Variable Latency : R²
Linear = 0.895
Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant # : 113

Condition
- BaselineLatency
- Variable Latency
- BaselineLatency
- Variable Latency

BaselineLatency : R²
Linear = 0.096
Variable Latency : R²
Linear = 0.859

Seconds per Hit
Number of Hits

Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant # : 114

Condition
- BaselineLatency
- Variable Latency
- BaselineLatency
- Variable Latency

BaselineLatency : R²
Linear = 0.928
Variable Latency : R²
Linear = 0.466

Seconds per Hit
Number of Hits
Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant # : 115

Condition
- BaselineLatency
- Variable Latency

BaselineLatency : R^2
Linear = 0.827
Variable Latency : R^2
Linear = 0.999

Number of Hits vs. Seconds per Hit

Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant # : 116

Condition
- BaselineLatency
- Variable Latency

BaselineLatency : R^2
Linear = 0.898
Variable Latency : R^2
Linear = 0.960

Number of Hits vs. Seconds per Hit
Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant # : 117

Condition
- BaselineLatency
- Variable Latency

BaselineLatency : R2
Linear = 0.974

Variable Latency : R2
Linear = 0.970

Number of Hits vs. Seconds per Hit

Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant # : 118

Condition
- BaselineLatency
- Variable Latency

BaselineLatency : R2
Linear = 0.871

Variable Latency : R2
Linear = 0.783

Number of Hits vs. Seconds per Hit
Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant #: 119

Condition
- Baseline Latency
- Variable Latency
- Baseline Latency
- Variable Latency

Baseline Latency: R²
Linear = 0.385
Variable Latency: R²
Linear = 0.823

Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant #: 120

Condition
- Baseline Latency
- Variable Latency
- Baseline Latency
- Variable Latency

Baseline Latency: R²
Linear = 0.950
Variable Latency: R²
Linear = 0.950
Individual Subjects Correlations
ACCURACY and TIME-TO-HIT
By Latency Condition

Participant #: 130

Condition
- Baseline Latency
- Variable Latency

Baseline Latency: R^2
Linear = 0.731

Variable Latency: R^2
Linear = 0.677

Number of Hits

Seconds per Hit
Appendix N
Analysis of Covariates

Summary of Appendix N: There is a significant effect of anxiety on sickness levels. This may be due to the similarity to items measured on the SSQ and the STAI-State questionnaires.

Analysis of Covariates on Sickness

Although there is no effect of sickness on condition, several factors were analyzed to examine their effects on sickness scores. Anxiety levels during the exposure to the stimuli were measured by the State-Trait Anxiety Inventory (State) and motion sickness susceptibility levels were measured by the MSSQ-S. Peak sickness scores were significantly correlated with both anxiety (Pearson’s $r$ (58) = .50, $p$ < .01) and susceptibility (Pearson’s $r$ (58) = .73, $p$ < .01). As a result, they were analyzed as covariates with a 2 (condition) X 6 (block) Repeated Measures ANCOVA. The ANCOVA revealed no main effects of condition, $F$ (1,52) = .00, $p$ = .98, $\eta^2_p$ = .00, a significant effect of anxiety, $F$ (1,52) = 27.82, $p$ < .01, $\eta^2_p$ = .35, and a significant effect of motion sickness susceptibility, $F$ (1,52) = 6.45, $p$ = .01, $\eta^2_p$ = .11. Controlling for anxiety and susceptibility did not change the lack of a main effect of condition reported above. The graph of peak sickness levels over time while controlling for anxiety and susceptibility is shown in Figure 3.4 below. Sickness and anxiety both measure similar items, therefore it is not surprising that this relationship was found, however the topic needs further examination to determine if the effects are independent.
Figure 3.4 Sickness levels across blocks of trials while controlling for anxiety and motion sickness susceptibility. The constant latency condition is labeled as “Baseline Latency” in this graph.
Summary of Appendix O: Questions arose as to whether the method used in the study resulted in independent measurement of time-to-hit. An alternative method is to sum the reaction times independent of corrections for misses. Using the alternate method, the independence of the measures improved, as the percentages of variance explained drop from 76.5% to 16.9% in the constant latency condition and from 88.6% to 8.4% in the varying latency condition.

In the main study time-to-hit was calculated by summing all times for all hits and misses obtained during a block of trials. Using this method, each miss counts for three seconds. The time-to-hit score was converted to a rate by dividing the total time value by 40 resulting in the number of seconds per hit for each block of trials. Although this method of accounting for misses is an acceptable method (Whelan, 2008), questions arose as to whether the method used in the study resulted in independent measurement of time-to-hit. An alternative method is to sum the reaction times independent of corrections for misses (Whelan, 2008).

The data were reexamined and the time-to-hit score for each block of trials was recalculated by summing the times for each hit. No adjustments were made for targets that were missed. The time-to-hit score was converted to a rate by dividing the total time for all hits by the number of hits. This revised method of scoring the time-to-hit dependent measure yields values that clearly highlight the differences between the latency conditions. The graph in Figure O.1 shows that the differences in time-to-hit between conditions remain with the revised method of calculating the time-to-hit score.
Figure O.1 Graph of time-to-hit over blocks of trials, by condition, without 3 seconds added for misses. The constant latency condition is labeled as “Baseline Latency” in this graph.

Figure O.2 below shows differences between the methods of determining time-to-hit graphically. The scatterplot on the left shows the relationship between accuracy and time-to-hit as it currently appears in the manuscript. The plot on the right shows the relationship between accuracy and time-to-hit using the values for time-to-hit derived without counting time for missed targets. As you can clearly see, determining time-to-hit using without including times for missed targets highlights the differences between latency conditions. Using the alternate method, the independence of the measures
improved, as the percentages of variance explained drop from 76.5% to 16.9% in the constant latency condition and from 88.6% to 8.4% in the varying latency condition.

**Figure O.2** Scatterplots of accuracy and time-to-hit showing the of calculating time-to-hit using two different methods. The plot on the left shows the data as it appears in the manuscript and the plot on the right shows the data with time-to-hit calculated without adding 3 seconds for misses. In both graphs the constant latency condition is labeled as “Baseline Latency”.
Appendix P
Analysis of MSAQ Data

**Summary of Appendix P:** This appendix provides the analysis of sickness levels in each condition based on the MSAQ. Sickness levels were assessed with both the SSQ and MSAQ questionnaires. The analyses in the main document were conducted on the SSQ values as the SSQ was administered prior to beginning the trials and after each block of trials was completed. The MSAQ was only administered before and after all trials. There was no effect of condition found using the MSAQ.

The MSAQ data were first examined for normality. The results of the Shapiro-Wilk normality test indicated that the pre-trial MSAQ scores were not normally distributed, $W(58) = .60, p < .01$, as shown in Figure P.1 below. As computed by IBM SPSS Statistics for Windows (IBM Corp. Released 2013. Version 22.0. Armonk, NY: IBM Corp.), outliers are depicted for values above or below the “whiskers” with two markers. Outliers between 1.5 X Inter-quartile Range (IQR) and 3 x IQR from the edge of the box are shown with a circle symbol “o”. Outliers more than 3 x IQR from the edge of the box are shown with an asterisk symbol “*” and referred to as extreme values. Three outliers and two extreme values were identified and can be seen in Figure P.1 below.
The histogram on the left shows the distribution of pre-trial MSAQ scores for both conditions for all 29 participants showing positive skewness. The boxplot on the right shows 5 outliers.

The distribution of the post-trial MSAQ scores were also not normally distributed, \( W(58) = .77, p < .01 \). The histogram of the post-trial MSAQ scores and the boxplot of the outliers are shown in figure P.2 below.
To correct the normality issue, a square root transformation (Bland & Altman, 1996) was performed on both pre-trial and post-trial MSAQ data to adjust for the skewness and kurtosis. Although more normally distributed, the Shapio-Wilk test results indicate that the both sets of data are still not normally distributed, pre-trial MSAQ, \( W(58) = .85, p < .01 \) and post-trial MSAQ, \( W(58) = .71, p < .01 \). The distribution of SQRT(Pre MSAQ) and SQRT(Post MSAQ) scores and the remaining outliers can be seen in Figures P.3 and P.4 respectively.

Figure P.2 The histogram on the left shows the distribution of post-trial MSAQ scores for both conditions for all 29 participants showing positive skewness. The boxplot on the right shows 4 outliers.
Figure P.3 The histogram on the left shows the distribution of SQRT(Pre MSAQ) scores for both conditions for all 29 participants showing positive skewness. The boxplot on the right shows 3 remaining outliers.

Figure P.4 The histogram on the left shows the distribution of SQRT(Post MSAQ) scores for both conditions for all 29 participants. The boxplot on the right shows 2 remaining outliers.
Sickness within each condition. The pre-trial and post-trial MSAQ scores were compared for each latency condition using a paired-samples t-test. For the constant latency condition, the mean sickness levels were $M = 3.76$ ($SD = 0.59$) pre-trial and progressed to $M = 4.51$ ($SD = 1.40$) post-trial. These values were found to be significantly different, $t(28) = 4.00$, $p < .01$ (1-tailed), $d = .70$. For the varying latency condition, the mean sickness levels were $M = 3.99$ ($SD = 0.95$) pre-trial and progressed to $M = 4.67$ ($SD = 1.39$) post-trial. These values were found to be significantly different, $t(28) = 4.30$, $p < .01$ (1-tailed), $d = .57$. This indicates that the sickness levels increased significantly during the experimental trials.

Sickness between conditions. The mean post-trial MSAQ scores for the constant latency ($M = 4.59$, $SD = 1.40$) and varying latency ($M = 4.67$, $SD = 1.40$) were compared using an independent samples t-test. Results indicated that there was no difference between the levels of sickness obtained during each latency condition, $t(56) = -.22$, $p = .42$ (1-tailed), $d = .06$. 
Summary of Appendix Q: Pilot testing was used to determine if there were differences in performance between conditions and how long it took to learn the performance task. The data is provided for future reference.

The current study benefitted from two pilot studies. In pilot study number 1, seven participants performed three trials each in three different conditions: No HMD, constant latency and varying latency. The results of the pilot study are shown in the graph in Figure Q.1 below. This study verified the premise that there is an accuracy difference in between conditions.

![Pilot Test 1](image)

*Figure Q.1 The results of pilot study 1 showing the difference in the number of hits by condition.*

The graph in Figure Q.2 below shows the results of pilot test number 2. Seven participants each performed 30 blocks of 40 trials each over a two-day period for a total of 1,200 total trials. Each participant performed 15 blocks, returned the following day, and completed 15 additional blocks. The graph in Figure Q.2 shows the mean number of hits per block of trials for the 7 subjects.
The results of pilot test number 2 are shown again, in Figure Q.3 below. In this chart, each participant is shown as a separate line across the 30 blocks of trials.

Figure Q.3 The results of pilot test 2 showing the number of hits per block of trials for each individual participant.
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