Frequency, Not Amplitude, of Latency Affects Subjective Sickness in a Head-Mounted Display

Amelia Kinsella; Ryan Mattfeld; Eric Muth; Adam Hoover

BACKGROUND: Interactions between frequency and amplitude of latency in head-mounted displays (HMDs) are thought to affect simulator sickness. Many studies have linked system latency to subjective sickness, but recent research has found that at least with the case of inertia-based head tracking technology, latency is not a constant; rather it varies systematically over time due to sensor errors and clock asynchronization. The purpose of this experiment was to further explore the relationship between frequency and amplitude of latency as they relate to subjective sickness experienced in an HMD.

METHODS: In a 2 (frequency) × 2 (amplitude) design, 120 subjects were randomly assigned to 4 latency conditions. Frequency of latency was either 0.2 Hz or 1.0 Hz. Amplitude of latency was either 100 ms fixed or 20-100 ms varying.

RESULTS: A main effect of frequency of latency was found. Subjects reported greater sickness in the 0.2-Hz frequency conditions (39.0 ± 27.8) compared to the 1-Hz conditions (30.3 ± 17.0). Additionally, 18 subjects withdrew their participation early in the 0.2-Hz conditions compared to 7 in the 1.0-Hz conditions.

DISCUSSION: In conclusion, frequency of latency appears to play a role in the experience of sickness in HMDs in both subjective reporting of symptoms and subject performance. The current study confirms results of earlier studies, finding that real motion around a frequency of 0.2 Hz is more sickening than other frequencies. Future work should continue to parse the effects of frequency and amplitude of latency in head-tracked HMDs.

KEYWORDS: frequency of latency, amplitude of latency, simulator sickness, head mounted displays.

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The purpose of this study was to examine the effect of varying latency in head mounted displays (HMDs) on subjective sickness. Specifically, we were interested in the independent effects of frequency and amplitude of latency as well as the interaction of frequency and amplitude on sickness. Latency is defined as the time between head movements and the resulting movement in the visual display. System latency is thought to be the main causal factor of simulator sickness in head tracked head-mounted display (HMD) based virtual environments. Recently, head tracker latency has been shown to vary over time, rather than remain constant.[13] It has been shown that varying latency, specifically amplitude of latency, leads to increased sickness,[11] but the independent effects of frequency and amplitude of latency and their interaction have not been examined.

Prior research has indicated system latency has the potential to cause sickness.[1,6] Previous studies using a head or motion tracked HMD have identified increasing constant latency as a cause of sickness.[1,5,6] However, our group[8] examined the effects of increasing constant latency on sickness in isolation from head tracking error. We used an HMD with a camera mounted on top, displaying a real world scene to distinguish the effects of latency from the effects of sensor error when using a motion tracker. In our paradigm, we did not observe an independent effect of increasing constant latency on sickness as others had previously reported when using head-tracked HMD paradigms.[1,5,6]

Recently, Wu, Dong, and Hoover [13] quantified the latency associated with inertial sensors typically used for head tracking applications and found that latency is variable due to a drift in sensor error. They found the drift to be within the range of 0.5 to 1.0 Hz with oscillations in amplitude of around 20-100 ms.

From Clemson University, Clemson, SC.

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Address correspondence to: Amelia Kinsella, 418 Brackett Hall, Clemson University, Clemson, SC, 29634; akinsel@g.clemson.edu.

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Throughout the rest of the paper, we will refer to aspects of latency using the following nomenclature described by St. Pierre and colleagues[11]: A, f, K, and B, where A = amplitude, f = frequency, K = constant, and B = base latency. In this study, B was a variable that was measured but could not be manipulated. If f = 0 or A = 0 then the latency is constant; otherwise the latency varies over time. We denote varying latencies by providing a range for A and/or f. For example, a latency of (A = 20-100 ms, f = 0.2 Hz, K = 120 ms, B = 70 ms) denotes a latency that changes amplitude to a random value between 20-100 ms at the start of each period of frequency.

Interestingly, in real-motion environments, the frequency of 0.2 Hz, a frequency near those identified to be caused by head tracker error,[13] has been found to be a particularly nauseogenic frequency. For example, O'Hanlon and McCauley[10] looked at the effects of vertical heave motion on motion sickness using a variety of different frequencies. They found peak sickness occurred at frequencies around 0.2 Hz. Numerous other studies involving real motion at or around this frequency of 0.2 Hz found similar results.[4,10,11] Previous research also found that sickness appears to decrease as frequency increases to 0.5 Hz, and this drop-off in nausea is known to continue to 1.0 Hz.[3]

St. Pierre and colleagues[11] examined the effect of varying latency on sickness in a noncrossed design using varying amplitude and this fixed frequency of 0.2 Hz. Specifically, four conditions were tested: baseline (A = 0, f = 0, K = 0 ms, B = 70 ms); constant (A = 0, f = 0, K = 200 ms, B = 70 ms); fixed frequency, fixed amplitude (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); and fixed frequency, varying amplitude (A = 20-100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms). St. Pierre et al.[11] tested 120 subjects who donned an HMD and completed an object location task requiring them to make head movements to find different objects around the laboratory. They found evidence for varying latency causing greater sickness symptoms than constant latency in HMDs (d = 0.64). Additionally, they found a significant increase in sickness when amplitude of latency varied compared to when it was fixed (d = 0.73). However, it is important to note that varying amplitude was only examined with the nauseogenic 0.2-Hz frequency; the independent effect of frequency and the interaction of amplitude and frequency were not examined. Thus, the purposes of the current study were to: 1) examine the independent effects of amplitude and frequency of latency; and 2) examine the interaction effects between frequency and amplitude of latency on sickness.

Four conditions with varying latency were tested. Based on evidence from St. Pierre et al.'s study,[11] we expected varying latency to result in greater sickness than constant latency. Therefore, all four conditions were expected to be sickening. The known sickening frequency of 0.2 Hz and a less sickening frequency of 1.0 Hz were crossed with fixed and varying amplitude of latency in a 2 (frequency) × 2 (amplitude) between-subjects design. A between-subjects design was chosen to avoid carryover effects between conditions among subjects and to reduce potential subject withdrawal between each condition.

The dependent variable was severity of sickness. The four experimental conditions were: 1.0-Hz frequency, fixed amplitude (A = 100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms); 1.0-Hz frequency, varying amplitude (A = 20-100 ms, f = 1.0 Hz, K = 100 ms, B = 70 ms); 0.2-Hz frequency, fixed amplitude (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms); and 0.2-Hz frequency, varying amplitude (A = 20-100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms).

Based on the literature surrounding the nauseogenic nature of the 0.2-Hz frequency, a main effect of frequency was hypothesized, i.e., there would be an increased level of sickness experienced when f = 0.2 Hz, compared to f = 1.0 Hz.[4,10,11] Based on St. Pierre et al.,[11] a main effect of amplitude was hypothesized, i.e., there would be an increased level of sickness experienced when amplitude was varying (A = 20-100 ms) compared to when amplitude was fixed (A = 100 ms).

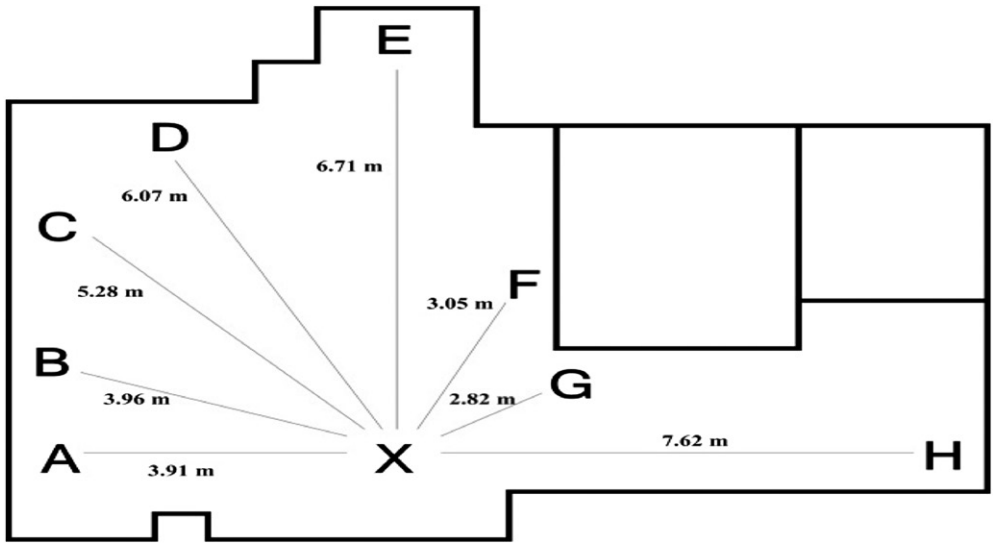

Fig. 1. Footprint of room layout for the object location task. X marks where the subject stood; A–H mark the objects the subject looked at during the experiment.

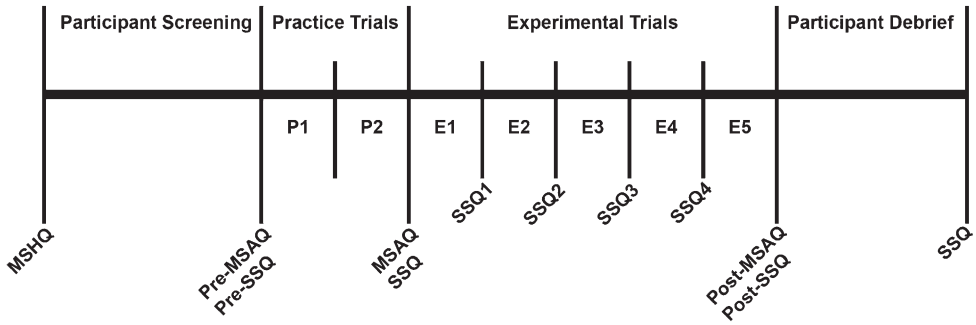

Fig. 2. Timeline representation of the procedure.

A significant interaction between frequency and amplitude was hypothesized, i.e., the 0.2-Hz frequency, varying amplitude condition would be the most sickening of the four conditions. Finally, it was hypothesized that there would be a significant effect of trial when looking at sickness symptoms over time, i.e., sickness would increase with increased exposure to the stimulus.

METHODS

Subjects

Recruited from Clemson University's student population were 120 subjects. Subjects were compensated for their participation and given course credit if applicable. All subjects read and signed a copy of the Clemson University Institutional Review Board approved informed consent form.

Equipment

Our experimental apparatus was first described in Moss and Muth.[8] In this system, an HMD is coupled with a video camera that is mounted atop the HMD. The video camera captures the real-world scene of the room the subject is in as they make head movements and move their visual point of view about the room. A frame-grabber integrated into a personal computer is put in the loop between the camera and the HMD. Locally developed software allows for images to be displayed immediately in the HMD or displayed with a fixed or variable amount of display. The software has been validated using an outside observer method.[13] It is important to note that our system does not include an inertial-based head tracker. The manipulation of the images through the software is meant to simulate the error behavior of the head tracker.

A ProView TM XL 50 HMD (Kaiser Electro-Optics, Inc., Carlsbad, CA) was used for this experiment. The XL 50 is a biocular HMD with a resolution of 1024 × 768 and a frame rate of 60 Hz. Rubber-like eye cups made specifically for the XL 50 were used to occlude external light from the environment. The HMD has a 50° field of view diagonally, 30° vertically, and 40° horizontally. It weighs 992 g.

A Uniq UC-610CL color digital CCD camera (Uniq Vision, Inc., Santa Clara, CA) was used to capture images of the real world. It was mounted atop the HMD. Resolution is 659 × 494 active pixels at a frame rate of 110 Hz. It uses a lens mount platform C-mount and a 1/3″ progressive scan CCD imager with R, G, and B primary color mosaic filters. The camera weighs 200 g.

A Dalsa X64 CL Express™ PCI camera link frame grabber (Teledyne Dalsa, Waterloo, ON, Canada) for image capture was installed on a Windows XP computer containing a 3.2-Ghz Pentium IV processor and 2 GB of RAM. A 256-Mb PCI Express™ video card was used. The real-world captured images from the camera were projected on the HMD and on the computer monitor for the experimenter to observe.

A custom delay program developed at Clemson University was used to generate varying latencies in the HMD. The outside observer method was employed to externally measure and validate the generated frequencies and amplitudes of latency.[13] Briefly, the procedure involved a camera as a sensor and the HMD as an actuator. A black bar was moved across a white background and a high-speed camera captured both the sensed and actuated images. Latency between sensed and actuated images was measured.

Two surveys were used to assess sickness symptoms. The Simulator Sickness Questionnaire (SSQ) was used to assess sickness symptoms before, during, and after the experiment.[8] This questionnaire requires subjects 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. The maximum Total Severity score is 235.62.

The Motion Sickness Assessment Questionnaire (MSAQ) is a multidimensional measure assessing motion sickness and was used to assess sickness symptoms before and after the experiment.[2] The MSAQ contains 16 items, and subjects responded to how they are feeling based on each item. Subjects responded using a 9-point scale (1 = not at all, 9 = severe) for each item. The maximum total score is 144.

Both symptom questionnaires used in this study have 16 items, with 4 items in common. The common items are: feeling nauseated, feeling tired/fatigued, sweating, and feeling dizzy.

Procedure

An object location task originally described by Moss and Muth[8] was used to challenge the subjects' visual-vestibular interaction. **Fig. 1** shows a footprint of the room layout during the experimental task. Subjects were required to look at eight distinct objects around the laboratory throughout the experiment (Fig. 1, A-H). Subjects stood in a predetermined location in the lab (Fig. 1, X), and remained standing for the duration of the experiment. The experimenter played a recording that gave subjects a direction and an object (e.g., "right, fire extinguisher"). Subjects made head movements while wearing the HMD to find the specified object. Subjects were asked to look at a different object every 3 s. The maximum horizontal movement encompassed by stimulus

Table I. Table of Peak SSQ Total Score Means, SD, and Sample Sizes for Each Condition.

	FREQUENCY		
	1 Hz	0.2 Hz	MARGINAL MEAN
Amplitude			
100 ms fixed	34.2 ± 25.3	48.6 ± 46.3	41.4 ± 37.7 (NS)
20–100 ms varying	48.5 ± 45.1	52.0 ± 45.2	50.2 ± 44.8 (NS)
Marginal Mean	41.3 ± 37.0 (NS)	50.3 ± 45.4 (NS)	

NS indicates "not significant."

arrangement was 180°. Subjects were instructed to make movements predominantly with their head and neck. If necessary, slight shoulder movements were allowed, but subjects were instructed not to make hip or leg movements during the task. Subjects were instructed to center the objects within the HMD display. In between trials, subjects were asked to look straight ahead at an 'X' placed directly opposite them. This simple head movement task is experienced as sickening by almost all subjects.

Fig. 2 shows an experimental procedure timeline. After signing informed consent, subjects were screened for a history of brain, heart, vision, stomach, or inner ear problems using self-report. Subjects were screened for pregnancy, vertigo, past experience with virtual environments and/or HMDs, and participating in vigorous exercise within the past hour using self-report. Subjects were screened for motion sickness susceptibility by verbally asking them "Do you easily get motion sick?" Any subjects answering yes to the previous screening questions were not permitted to participate. Subjects who reported feeling sick or less than their normal physical state were asked not to participate on that day and rescheduled for another session. Subjects were asked to abstain from alcohol, nicotine, and caffeine for 12 h prior to their appointment.

After screening, the experimenter explained the object location task and asked if the subject had any questions regarding this task. The subject was asked to stand in a specific spot and grasp a handrail placed in front of them for the duration of the experiment. They were told not to lock their knees during the experiment, as this can cause fainting. Next, the subject was assisted in donning and adjusting the HMD for fit such that the duplicate images separately presented to each eye merged into a single image. Once the HMD was adjusted appropriately, the experimenter verbally administered a pre-practice MSAQ and SSQ.

Each subject completed two 48-s practice trials with no manipulated latency. The practice trials were intended for the subject to become familiar with object locations and the speed of the task. After both practice trials, the experimenter verbally administered the MSAQ and SSQ.

The experiment entailed five 2-min trials with a 1-min break between trials. There were 40 head movements in each trial each separated by 3 s. During each trial, the experimenter recorded the accuracy of the head movements via a monitor displaying the projected images in the HMD. The experimenter verbally administered the SSQ during the break after each trial and the MSAQ at the end of the final trial while the subject was still wearing the HMD.

Prior to the start of the experiment, subjects were instructed that the goal of this study was not to make them feel too uncomfortable and if at any time they felt too uncomfortable they should notify the experimenter and the study would be stopped immediately. In between each trial, the experimenter asked the subject if they felt fit enough to continue with the experiment.

After completing five trials, the subject was asked to take off the HMD. The experimenter debriefed the subject on the purpose of the study and verbally administered the SSQ to make sure the subject was well enough to leave the lab.

RESULTS

Subjective sickness was calculated as the maximum (peak) SSQ score experienced by subjects during the experiment so that subjects who stopped HMD exposure early could still be included in the analysis. Means and SDs for peak SSQ scores in each condition were calculated for each subject (see **Table I**). A 2 (frequency) × 2 (amplitude) ANOVA was conducted to examine the main effects and interaction of frequency and amplitude on sickness. No significant main effects were found for frequency [$F(1, 116) = 1.41$, $P = 0.24$], amplitude [$F(1, 116) = 1.37$, $P = 0.24$], or interaction [$F(1, 116) = 0.53$, $P = 0.47$].

Post-trial SSQ scores were analyzed in addition to peak SSQ. Means and SDs were calculated for each condition from the post-trial SSQ score (see **Table II**). No significant main effects were found for frequency [$F(1, 116) = 1.58$, $P = 0.21$] or amplitude [$F(1, 116) = 1.54$, $P = 0.22$], and no significant interaction was observed [$F(1, 116) = 0.43$, $P = 0.52$].

Means and SDs for total MSAQ scores were calculated for each condition (see **Table III**). A 2 (frequency) × 2 (amplitude) ANOVA was conducted to examine the main effects and interaction of frequency and amplitude on motion sickness. A significant main effect of frequency of latency was found [$F(1, 116) = 4.19$, $P = 0.043$, $\eta^2 = 0.035$]. No significant main effects were found for amplitude

Table II. Post-Trial SSQ Score Means and SDs by Condition.

	FREQUENCY		
	1 Hz	0.2 Hz	MARGINAL MEAN
Amplitude			
100 ms fixed	31.8 ± 25.9	46.4 ± 46.0	39.1 ± 37.7 (NS)
20–100 ms varying	46.3 ± 45.6	50.9 ± 446.3	48.6 ± 45.6 (NS)
Marginal Mean	39.0 ± 37.5 (NS)	48.6 ± 45.8 (NS)	

NS indicates "not significant."

Table III. Table of MSAQ Total Score Means and SDs for Each Condition.

	FREQUENCY		
	1 Hz	0.2 Hz	MARGINAL MEAN
Amplitude			
100 ms fixed	28.3 ± 12.2	39.3 ± 27.9	33.9 ± 22.0 (NS)
20–100 ms varying	32.3 ± 20.8	38.6 ± 28.2	35.5 ± 24.8 (NS)
Marginal Mean	30.3 ± 17.0*	39.0 ± 27.8*	

* Indicates significance; (NS) indicates "not significant."

of latency [$F(1, 116) = 0.14$, $P = 0.71$] or interaction between frequency and amplitude of latency [$F(1, 116) = 0.30$, $P = 0.58$].

To examine if symptoms worsened over time, a condition by trial repeated measures ANOVA was conducted. The analysis was completed on the 95 subjects who completed all five experimental trials. **Fig. 3** shows a graph of average SSQ total scores across the five trials for each condition. A significant main effect of trial was found [$F(1, 91) = 64.66$, $P < 0.01$, $\eta^2 = 0.42$]. No significant main effect of condition was found [$F(1, 91) = 0.532$, $P = 0.66$]. No significant interaction was found between trial and condition [$F(1, 91) = 0.24$, $P = 0.87$].

There were 25 subjects who were unable to complete the 5 trials and withdrew early from HMD exposure. Expected cell counts were low (near 5); therefore, a Fisher's exact test was computed to examine effects of frequency and amplitude on subject withdrawal. Data were collapsed across the two frequency conditions to look for an effect of amplitude, resulting in 11/60 subjects withdrawing early from the fixed amplitude conditions and 14/60 subjects withdrawing early from the varying amplitude conditions, a not statistically significant difference ($P = 0.33$, Fisher's Exact Test). Data were also collapsed across the two amplitude conditions to look for an effect of frequency, resulting in 7/60 subjects withdrawing early from the 1.0-Hz conditions and 18/60 subjects withdrawing early from the 0.2-Hz conditions, revealing a significant effect of frequency ($P = 0.011$, Fisher's Exact Test).

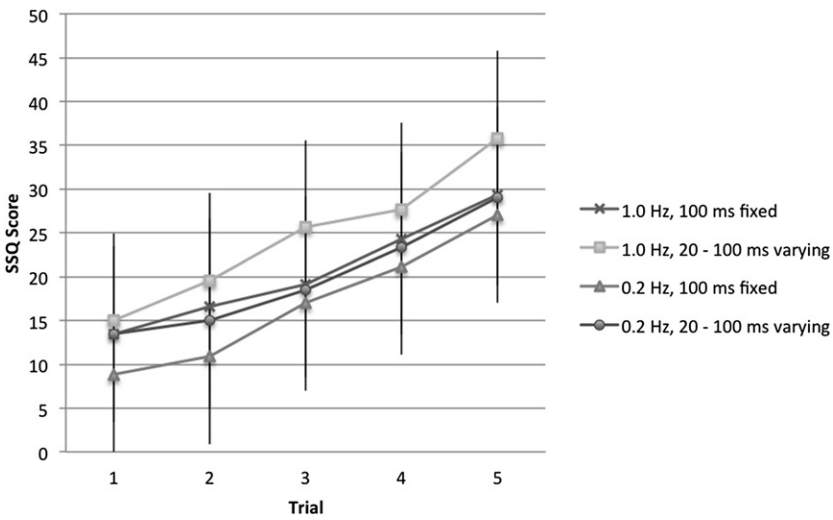

Fig. 3. Line graph of average SSQ total scores across experimental trials for each condition.

DISCUSSION

The purpose of this study was to examine the independent effects of frequency and amplitude of latency and their interaction effects on simulator sickness. The current study provides support for our hypothesis that there would be an independent effect of frequency of latency on sickness, but does not provide support for the hypotheses regarding an independent effect of amplitude of latency, or interaction effect of frequency and amplitude.

A main effect of frequency of latency on sickness was found, such that subjects experienced more severe sickness symptoms in the 0.2-Hz conditions than in the 1.0-Hz conditions. The magnitude of this effect was small and the effect was detected only for MSAQ scores and not peak or post-trial SSQ scores. Nonetheless, results from all questionnaires trended in the same direction. Additionally, there was no significant interaction between frequency and amplitude, suggesting any effects of frequency on sickness are independent. This finding partially replicated the main effect of frequency from St. Pierre et al.'s study.[11] However, in the previous study, there was a main effect of frequency found for both MSAQ and SSQ scores. Additionally, the effect sizes for St. Pierre et al.'s study ($d = 0.67$, MSAQ; $d = 0.64$, SSQ) were stronger than those in the current study ($d = 0.38$, MSAQ; $d = 0.21$, SSQ). It is important to note that the current study compared two different frequencies and the previous study compared one frequency to constant latency.

A main effect of frequency on subject withdrawal was also observed. Overall, 21% of subjects withdrew from HMD exposure early. Recall that strong history of motion sickness was an exclusion criterion for participation. Hence, a 21% dropout rate on this simple object location task is indicative of the sickening nature of the stimulus regardless of condition. However, significantly more subjects in the 0.2-Hz conditions prematurely ended their participation in the experiment than those in the 1.0-Hz conditions, further supporting previous research suggesting an effect of frequency on sickness.[11] Additionally, no significant effect of amplitude on subject withdrawal was found. These results are interesting because they suggest the effects of frequency can show up in different measures in both self-reported symptom questionnaires and subject performance.

This main effect of frequency of latency contributes to the already existing body of research reporting the 0.2-Hz frequency to be sickening to humans.[4,10,11] The effect of frequency on subject withdrawal rate is a possible explanation for why the current experiment did not fully replicate St. Pierre et al.'s results[11] in which an effect of varying vs. constant amplitude was observed in addition to, but not

independent of, the frequency effects. St. Pierre and colleagues only included one 0.2-Hz frequency condition in their study and had fewer subjects withdraw from the experiment early than the current experiment. Since more subjects were able to complete all five experimental trials in St. Pierre et al.'s study[11] than in the current study, subjects could have experienced more severe symptoms simply because they were experiencing the stimulus for a longer period of time. Had all (or more) subjects completed the current experiment, it is possible that symptom severity would have been significantly higher in the 0.2-Hz frequency conditions due to greater exposure to the stimulus. Then the effect sizes from the current study might be more comparable to those found by St. Pierre and colleagues. Since 25 subjects did not complete the entire experiment, their symptoms may not have reached their maximum. Withdrawal rate could have been tied to an effect of gender of the experimenter (female in this study and male in the previous study), which the current study was not designed to assess.

The discrepancy between MSAQ and SSQ results could be due to the different dimensionalities of the questionnaires, measuring two slightly different syndromes (motion sickness and simulator sickness), or the fact that they were administered at different times throughout the experiment. The hypothesis predicting there would be increased sickness symptoms with increased duration of exposure to stimulus was supported. All four conditions caused severity of symptoms to increase over time, aligning with previous research.[9,11]

This experiment further supports the importance of varying latency as a contributor to sickness in head-tracked HMDs. In order to better design systems in the future, a full understanding of how the variance in latency contributes to sickness is needed. Future studies should include additional frequency and amplitude conditions. In addition, effects of the interaction of experimenter gender with subject gender should be assessed. A within-subjects design should be considered to control for individual differences in susceptibility. With this design, we can also examine the possible interaction between adaptation to constant and varying latency, as presumably humans are better able to adapt to constant perceptual perturbations than varying ones[12]. Further, task performance under varying latency conditions should be examined. Taking together the results of the current work and the findings of Moss and Muth[8] and St. Pierre et al.,[11] it is becoming clearer that constant latency is not the causal factor in HMD sickness, but rather varying latency in which the variance of the frequency of latency seems critical, and amplitude may also play a role.

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Authors and affiliation: Amelia Kinsella, M.S., Ryan Mattfeld, M.S., Eric Muth, Ph.D., and Adam Hoover, Ph.D., Clemson University, Clemson, SC.

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