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The effects of 0.2 Hz varying latency with 20–100 ms varying amplitude on simulator sickness in a helmet mounted display

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ABSTRACT

The relationship between the occurrence of simulator sickness (SS) and varying latency in a helmet-mounted display (HMD) was explored in this study. Previous work has always considered latency to be a constant. The aim of this research was to determine if a latency that varied over time would impact the experience of SS for HMD users. An object location task was used while viewing real, live video scenes via HMD. A planned comparisons approach was utilized with four experimental conditions, 2 of them having constant latency (0 ms added to system baseline, 200 ms added to system baseline) and 2 of them having sinusoidally varying latency (100 ms amplitude at 0.2 Hz frequency, and 20–100 ms varying amplitude at 0.2 Hz frequency). These conditions allowed for the assessment of the effects of constant latency vs. varying latency on the experience of SS. The results indicated that a varying latency is associated with greater experience of SS among HMD users than constant latency. Results also indicated, as has other recent research, that added constant latency on its own does not appear to be associated with the experience of higher levels of SS in an HMD.

1. Introduction

The purpose of the current study was to assess the relationship between time-varying latency in a helmet mounted display (HMD) and simulator sickness (SS). Previous work has focused on constant latency and the effects of varying latency over time have not been examined in HMDs. However, time-varying stimuli have been shown to influence motion sickness (MS) in non-virtual environment (VE) situations [1]. In particular, this study examines the inherent base latency of the HMD system, compared to constant additional latency and latency varying sinusoidally over time.

SS commonly occurs in VEs, including those with HMDs as the visual interface. A variety of potential variables influencing the experience of SS in HMD based VEs have been proposed, including system latency [2–5], field of view [3], image scale factor [6], and occlusion of peripheral vision [7].

Latency has received the most attention as a possible factor influencing the experience of SS in HMD VEs. Latency in HMD VEs refers to the time between a head movement and change in the depiction of the environment in the visual display. Latency is associated with the computational processes that occur in reaction to, and to compensate for, actions of the user. In a flight simulator study, Wildzunas et al. [2] found that latencies greater than 267 ms were most perceptible to participants and a 533 ms latency condition presented a significant increase in motion sickness (MS) symptoms as compared to conditions with lower latency (i.e., 400 ms, 267 ms, 133 ms, and 67 ms). An HMD study by DiZio and Lackner [3] had participants make 24 head movements in the range of 12–180° over 2 min intervals at different levels of latency. This sequence was repeated five times with 1 min breaks between. Participants experienced significant sickness in all latency conditions and significant increases in sickness as the latency increased. HMD studies by Jennings et al. [4,5] had participants wear an HMD with different latency levels while performing a hovering task in a simulator. Participants in both studies experienced MS symptoms such as eye strain, vertigo, dizziness, and nausea with an increase in symptoms as latency increased. All of these studies employed a head tracker or motion tracker of some kind.

Moss and Muth [7] sought to isolate the effects of latency from the effects of sensor error associated with motion trackers. They used an experimental setup with an HMD and a camera mounted

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on top as the sensor. Images from the real world laboratory environment were captured by the camera and participants were asked to locate objects in the environment. Participant experience of SS was measured between each experimental trial. Participants were exposed to either 0 ms added latency or 200 ms added latency. Unlike previous studies using motion trackers, Moss and Muth found no significant relationship between the experience of SS and exposure to added constant latency. These findings did not support prior research on the relationship between SS and added latency, indicating that something more than addition latency may be affecting participant SS.

A study by Wu et al. [8] measured the latency of a system using a magnetometer–accelerometer–gyroscope sensor of the type for tracking orientation that is commonly used in HMDs. Unlike previous works which relied upon averages of measurements, the latency was measured continuously at 1 ms resolution in order to observe how it varied over time. Results showed that the latency had an apparent drift over time due to sensor error. The observed latency drift varied at frequencies from 0.5 to 1.0 Hz with amplitude of approximately 20–100 ms. These frequencies fall within the same range known to provoke MS using horizontal oscillations [9–11] and vertical oscillations [1,12–14] in non-VE, real world environments. It was hypothesized that varying latency due to head tracker error may explain the differences in findings regarding SS associations with latency in head tracked HMDs vs. non head tracked HMDs.

1.1. Current study

The purpose of the current study was to examine the relationship between system latency varying over time in HMDs and the experience of SS, which is a previously unexplored relationship in HMD VE research.

A baseline condition in which the only system latency present is a constant was considered to represent a system without a head-tracker. An added constant latency condition was considered to control for the simple addition of latency without the presence of varying latency due to a head tracker. Motivated by conflicting prior research regarding the role of added latency in HMD VEs and the findings by Wu et al. [8] that head tracker error introduces variations in the frequency of latency in ranges previously associated with MS prompted the question "is the result of the sensing error on the perception of the visual scene a variable that influences the experience SS in HMDs?" Hence, two sinusoidally varying latency conditions (100 ms fixed amplitude at 0.2 Hz fixed frequency, and 20–100 ms varying amplitude at 0.2 Hz fixed frequency) were used to assess the effects of constant latency vs. varying latency on the experience of SS.

Based on the results of Moss and Muth [7], where simply adding latency was not associated with an increase SS and that the current added latency condition replicated the one used by Moss and Muth [7], it was hypothesized that added constant latency alone would not be significantly different than base latency. However, conditions with varying latency, which were used to simulate conditions where a head tracker is present, were hypothesized to yield a significantly higher level of SS compared to both base latency and constant additional latency (200 ms) conditions.

2. Method

2.1. Participants

Participants were 120 individuals (56 male) responding to flyers advertising the study and posted in various locations on Clemson University's campus. Additional participants were recruited using the Psychology Department's subject pool at Clemson University. Those responding to the on-campus flyer received $10 per hour while participants from the subject pool were given course credit as well as $10 per hour compensation. Those who self-reported a history of severe motion sickness, heart, brain, visual (other than corrected vision) or inner ear problems were excluded from participation. Females self-reporting being pregnant were also ineligible for participation. Individuals with corrected vision who did not have or wear contact lenses were ineligible to participate because the use of glasses prevented optimal HMD fit. This study was approved by the Clemson University Institutional Review Board and all participants signed an informed consent form prior to participating.

2.2. Materials and apparatus

A Uniq *UC-610CL* color digital CCD camera was used to capture images from the laboratory environment in this study with a frame rate of 110 Hz. This device was mounted atop a Kaiser Electro-Optics, Inc., *ProViewTM XL 50* HMD. HMD resolution was 1024×768 at a frame rate of 60 Hz. The HMD prior to camera mount weighed 35 oz (42.05 oz with camera) with a 50° field of view (FOV) diagonally, 30° FOV vertically, and 40° horizontally. Since only a single camera was used, the HMD was configured to display the same image simultaneously to both eyes (bi-ocular). A Dalsa *X64 CL Express*™ PCI camera link frame grabber for image capture was installed on a Windows XP computer using a 3.2 GHz *Pentium IV* processor and 2 GB of RAM. A 256 Mb *PCI Express*™ video card was used to drive the display. In addition, eye cups were fixed to the HMD to occlude peripheral vision.

A custom program for the manipulation of latency was written using the Dalsa *Sapera*™ *LT* library. The program manipulated latency by buffering captured images in integral units of the frame capture rate (1/110 Hz = 9 ms). A constant buffer size was used to add a constant latency (e.g., 0 frames buffered = 0 ms added constant latency; 22 frames buffered = 200 ms added constant latency). A varying buffer size was used to add a varying latency, where the amount of frames buffered varied over time to fit the desired sinusoidal pattern.

To confirm the manipulations of latency (constant added latencies, and amplitude and frequency of varied latencies), the methodology in Wu et al. [8] was used. This process consisted of using a high speed camera (Fastec Trouble Shooter 1000) to simultaneously observe a live event and its depiction in the HMD. The event was the motion of a vertical black stripe horizontally from a right vertical stripe to a left vertical stripe. The high speed camera captured video at 480×640 resolution at 1000 Hz for up to 4.4 s. To confirm the amplitude and frequency of latency manipulations were as intended for the proposed conditions, ten recordings were collected for five separate conditions (baseline, baseline + 200 ms, 0.2 Hz with 30 ms amplitude, 0.2 Hz with 60 ms amplitude, and 0.2 Hz with 100 ms amplitude). When analyzed, these recordings confirmed the latencies were behaving as expected.

2.3. Latency

In the current study, latencies that varied over time were examined, and compared to latencies that remain constant over time. All latencies can be written as:

$$\text{Latency}\ (t) = A\ \sin\ (2\pi f t) + K + B$$

where B is the existing system baseline latency, and the remaining terms denote added latency. This formula can be used to describe both constant and sinusoidally varying latencies. If $f = 0$ or $A = 0$ then the latency is constant; otherwise the latency varies sinusoidally over time. A given latency can be described by providing

values for (A, f, K, B). In this study, B was a value that was measured, but could not be manipulated. Terms A, f, K were manipulated. For example, a latency of (A = 0, f = 0, K = 120 ms, B = 70 ms) refers to a constant latency of 190 ms. A latency of (A = 50 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms) refers to a sinusoidal latency with an average of 170 ms, amplitude of 50 ms and frequency of 0.2 Hz. Note that the combination of baseline and constant must always be larger than the amplitude because we do not consider cases where the latency can be negative. Latencies were also examined where the frequency and amplitude are varied period to period. These were denoted by providing a range for A and/or f. For example, a latency of (A = 20–100 ms, f = 0.2 Hz, K = 120, B = 70 ms) denotes a latency that changes amplitude to a random value between 20 and 100 ms at the start of each period.

2.4. Design

This current study was a between-subjects design consisting of four conditions. Each condition contained 70 ms of constant baseline system latency. The independent variables were added latency, and frequency and amplitude of latency. Levels of added latency were 0 ms and 200 ms. Levels of frequency of latency were either 0 Hz or 0.2 Hz. Levels of amplitude of latency were either constant at 100 ms or varying at 20–100 ms. Condition 1 was the baseline condition (A = 0, f = 0, K = 0 ms, B = 70 ms), condition two was the constant condition (A = 0, f = 0, K = 200 ms, B = 70 ms), condition three was the fixed frequency, fixed amplitude condition (A = 100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms), and condition four was the fixed frequency, varying amplitude condition (A = 20–100 ms, f = 0.2 Hz, K = 100 ms, B = 70 ms). A list of these conditions, their parameters, and what they simulate can be found in Table 1. Visual representations of amplitude of latency conditions are shown in Figs. 1 and 2. Participants were pseudo-randomly assigned to ensure an equal gender distribution in each condition. Multiple dependent variables were measured in the current study. SS was measured using the Simulator Sickness Questionnaire [SSQ; 15] and MS was measured using the Motion Sickness Assessment Questionnaire [MSAQ; 16].

2.5. Experimental task

Participants in this study performed an object location task while wearing an HMD. Fig. 3 depicts the relative locations of the eight objects. Head movements were made to locate the objects in the laboratory based on the name and direction of the object (e.g., "right curtain") which were called out by a voice recording in 3 s intervals. All head movements were at or near head height in the horizontal plane left and right of center and no more than 90° left and 90° right. The largest horizontal head movement was 180° and participants were instructed to make head movements primarily from the head and neck.

Participants faced forward to begin the trial with the front door (F) approximately in the center of the display. Objects were randomized into five 2 min trials with 40 head movements per trial. Participants were instructed when located an object to center it in their display. The last head movement in each trial returned participants to the starting position. A 1 min break from head movements was provided between each trial.

2.6. Procedure

After arriving to the lab, participants completed a Clemson University Institutional Review Board approved informed consent form. Participants were then screened for eligibility for participation. Participants' visual acuity was screened using a LogMAR chart. Participants MS history was also taken using the MSHQ. Individuals who reported a severe history of motion sickness, i.e., experiencing MS symptoms frequently or easily, were excluded from the study.

Participants were then led to the back of the lab to measure their inter-pupillary distance (IPD). This measurement was in centimeters (cm) and was used as the set distance between the two displays on the HMD. This was done rather than letting the participant set the distance between the displays themselves in order to prevent unnaturally convergent or divergent viewing situations for the participant.

After the IPD measurement was collected, participants were shown where to stand during the object location task. The procedures for the object location were explained to the participants. The objects involved in the task were identified prior to beginning the task so the participant could locate them. Participants were provided a 39.75″ step ladder they used as a handrail to support balance during the experimental trials. The participant then donned the HMD and the distance between the center of each display was adjusted to match the IPD of the participant. The lens cap of the high speed camera was then removed and the participant was asked to assess the visual scene for any focus adjustments needed to the camera to improve image quality. Adjustments were made, if necessary, then the lens cap was placed back on the camera. A pre-practice MSAQ and SSQ was then administered to the participant.

Participants performed two 48 s practice trials to familiarize themselves with the experimental task. After completing the practice trials, another MSAQ and SSQ were administered to the participant.

The participants then performed 5 experimental trials. Each trial was 2 min long with a head movement made every 3 s. There was a 1 min break between trials. Accuracy of the head movements were tracked by viewing the images projected in the displays of the HMD on the computer monitor. Accuracy of head movements were tracked to insure that the participants were viewing the correct objects, making the correct head movements, and performing the task correctly. Head movements were not used to perform any analyses. During the 1 min breaks between trials, an SSQ was administered. Following the final trial, the MSAQ and SSQ were administered while the participant was still wearing the HMD. SSQs were also administered 5 and 10 min after completion of the trials to check for recovery before releasing the participant.

3. Results

3.1. Peak sickness

To avoid excessive dropouts and to maintain equal cell sizes, the peak SSQ obtained from each participant was used to analyze the relationship between the experience of SS and manipulations of

Table 1
List of conditions and their latency characteristics. Latencies are in milliseconds and frequencies in Hz.

Condition	Frequency (Hz)	Amplitude (ms)	Base latency (ms)	Added latency (ms)	Total latency (ms)	Simulates
Baseline	0	0	70	0	70	Non-head tracked VE
Constant	0	0	70	200	270	Non-head tracked VE with added latency
Fixed	0.2	100	70	100	70–270	Head tracked HMD
Varying	0.2	20–100	70	100	70–270	Head tracked HMD

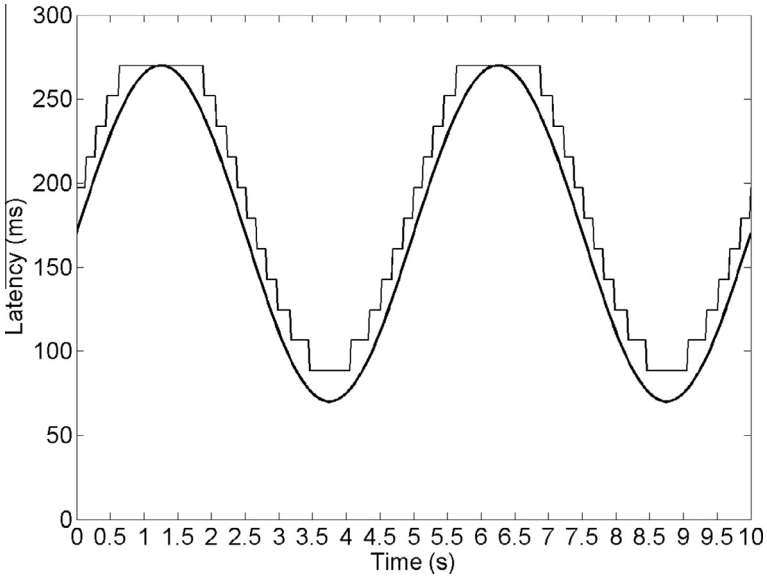

Fig. 1. Fixed amplitude condition consisting of 100 ms amplitude at 0.2 Hz.

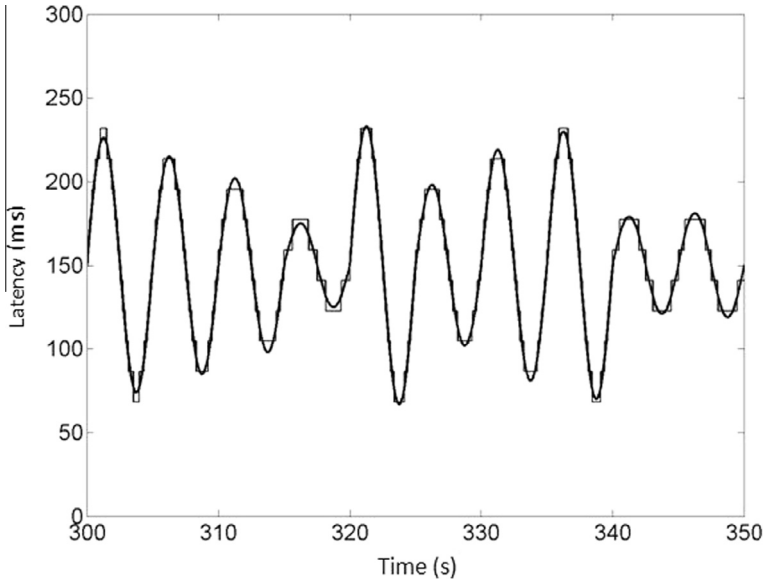

Fig. 2. Varying amplitude condition consisting of 20–100 ms amplitude at 0.2 Hz.

latency in the HMD. Post experimental MSAQ measurements were used to analyze the same relationship with MS and manipulations of latency in the HMD. Peak SSQ scores were collected from 120 participants, 11 of who withdrew from the experiment before completion of all 5 experimental trials. All participants who withdrew experienced common symptoms associated with SS (i.e., dizziness, nausea, headache, oculomotor symptoms, etc). Four of these participants reported severe faint-like symptoms. Two of the participants opted to lie on the floor until faint-like symptoms subsided. During the debriefing, these 4 participants reported never experiencing similar symptoms in the past.

There were a total of four conditions in the current study. Each condition contained a total of 40 participants. Peak SSQ scores were used for the following analysis so individuals who withdrew early could be retained in the analysis. The effects of added latency, frequency, and amplitude of latency on peak SSQ scores were assessed using a series of planned comparisons using independent samples *t*-tests. In the case where samples being compared via *t*-test had unequal variances, the degrees of freedom correction for unequal variances was employed. An independent samples *t*-test was performed between the baseline and constant latency conditions. The independent samples *t*-test revealed that the peak SSQ scores in the baseline condition ($M = 24.19$, $SD = 24.55$) were lower than those in the constant latency condition ($M = 27.43$, $SD = 32.87$), but this difference did not reach statistical significance $t(58) = -0.43$, $p = 0.67$. An independent samples *t*-test was performed between the fixed amplitude and varying amplitude conditions. The independent samples *t*-test revealed that the peak SSQ scores in the fixed amplitude condition ($M = 34.53$, $SD = 33.52$) were lower than those in the varying amplitude condition ($M = 60.84$, $SD = 41.22$) and this difference was significant $t(58) = -2.71$, $p = 0.01$, see Fig. 4. An independent samples *t*-test was performed to compare 0 Hz frequency condition (i.e., combination of the baseline and constant conditions) and the 0.2 Hz

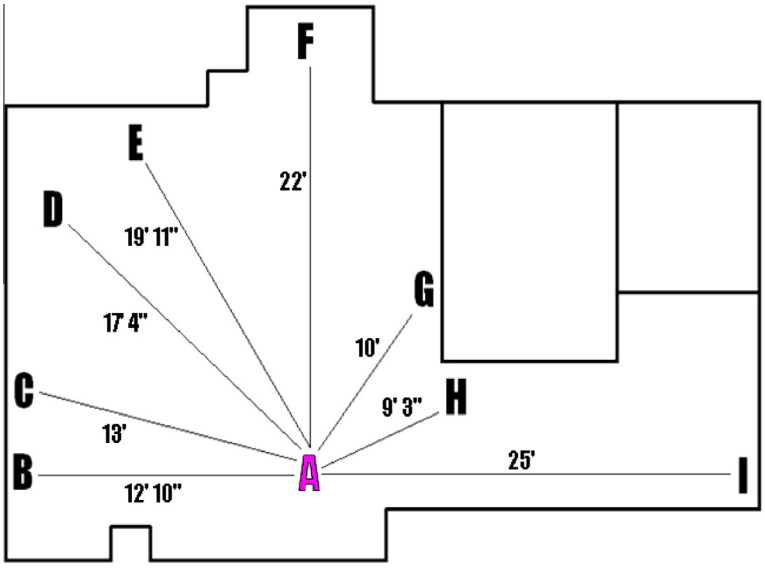

Fig. 3. Room layout with distance measurements from the participant. A = Participant, B = Office door, C = Clock, D = Flag, E = Photocopy of fire extinguisher, F = Front door, G = First aid, H = Fan, I = Curtain [17].

frequency condition (i.e., combination of the fixed amplitude and varying amplitude conditions). The independent samples *t*-test revealed that the peak SSQ scores in the 0 Hz frequency condition ($M = 25.81$, $SD = 28.81$) were lower than those in the 0.2 Hz condition ($M = 47.69$, $SD = 39.54$) and this difference was significant $t(108) = -3.46$, $p < 0.001$, see Fig. 5.

The same approach was also used to analyze post experimental MSAQ scores. An independent samples *t*-test was performed between the baseline and constant latency conditions. The independent samples *t*-test revealed that the MSAQ scores in the baseline condition ($M = 25.13$, $SD = 11.08$) were lower than those in the constant latency condition ($M = 27.87$, $SD = 18.58$), but this difference did not reach statistical significance $t(58) = -0.69$, $p = 0.49$. An independent samples *t*-test was performed between the fixed amplitude and varying amplitude conditions. The independent samples *t*-test revealed that the MSAQ scores in the fixed amplitude condition ($M = 32.23$, $SD = 19.77$) were lower than those in the varying amplitude condition ($M = 48.77$, $SD = 27.31$) and this difference was significant $t(58) = -2.69$, $p = 0.01$. An independent samples *t*-test was performed between 0 Hz and the 0.2 Hz frequency conditions. The independent samples *t*-test revealed that the MSAQ scores in the 0 Hz frequency condition ($M = 26.50$, $SD = 15.23$) were lower than those in the 0.2 Hz condition ($M = 40.50$, $SD = 25.07$) and this difference was significant $t(97) = -3.70$, $p < 0.001$.

3.2. Participant withdrawal

Due to the high number of participants (11/120 = 9.2%) who withdrew from the experiment, participant withdrawal was examined. Participant withdraw was defined as any time a participant dropped out of the experiment prior to completion of all 5 experimental trials. This analysis included all 120 participants, 30 participants being present in each of the 4 conditions. A total of 11 participants withdrew from the experiment prior to completion of the 5 experimental trials. Seven participants withdrew following the varying amplitude condition, 2 withdrew after the constant condition and 2 after the fixed amplitude condition. No-one withdrew following exposure to the baseline condition.

A 2×4 chi-square test of independence was performed. The test indicated a significant relationship between condition and participant withdrawal, $\chi^2(3, N = 120) = 10.71$, $p = 0.013$. The χ^2 expected cell count assumption was violated because all four cells (50.0%) had an expected count at less than five. As a result, Fisher's

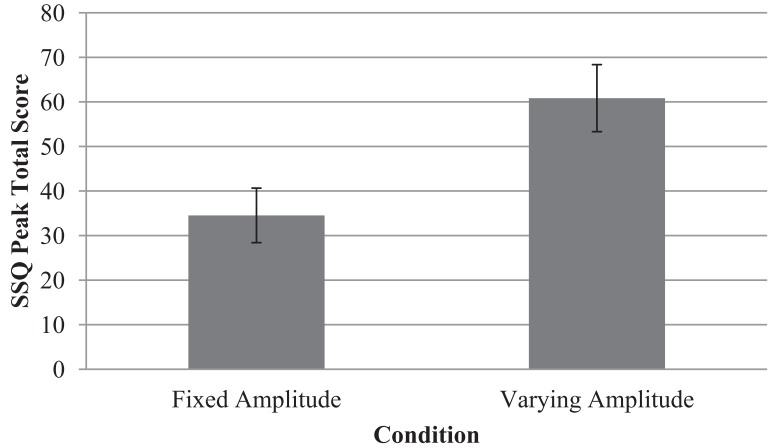

Fig. 4. Mean difference between peak SSQ scores in the fixed amplitude and varying amplitude conditions with standard error bars.

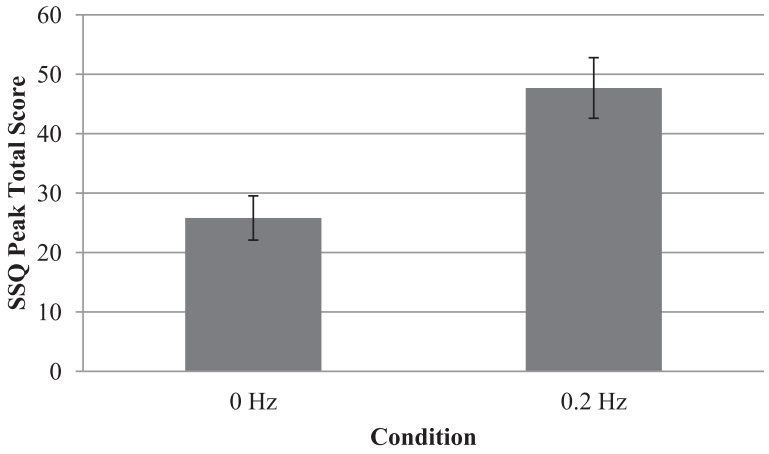

Fig. 5. Mean difference between peak SSQ scores in the 0 Hz and 0.2 Hz conditions with standard error bars.

exact test was performed. It was found that condition membership was related to participant withdraw (3, $N = 120$, $p = 0.013$, two-tailed Fisher's exact test).

3.3. Effect of trial on sickness

A 4 (condition) × 5 (trial) repeated measures ANOVA was performed across conditions to determine the effects of trial on sickness. This analysis was performed using SSQ scores gathered from participants immediately after each experimental trial. Only those participants that completed all trials were included in this analysis. As such, this analysis ignored condition in order to just look at time of HMD exposure.

Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(9) = 191.26$, $p < 0.001$. Degrees of freedom were corrected using the Greenhouse–Geisser estimates of sphericity, $\varepsilon = 0.52$. Results indicated a significant effect of trial on SSQ scores, $F(2.06, 222.58) = 59.83$, $p < 0.001$. This indicated an increase in SSQ scores across trials, see Fig. 6.

Post hoc pairwise comparisons using Holm's sequential Bonferroni approach indicated significant differences between all experimental trials. Mean SSQ scores for all trials were significantly higher when compared to the trials that preceded them (e.g., significantly higher mean SSQ scores for trial 4 as compared to trials 3, 2, and 1).

4. Discussion

The analyses of peak SSQ and post experimental MSAQ scores yielded similar results for latency manipulations. Support was found for the hypothesis that frequency of latency of 0.2 Hz would yield higher sickness than frequency of 0 Hz. When collapsing the 0.2 Hz conditions (i.e., fixed amplitude and varying amplitude), higher peak SSQ scores and MSAQ scores were observed than when the 0 Hz conditions were collapsed (i.e., baseline and constant). No previous studies exist regarding the relationship between frequency of latency and SS in an HMD. Previous research regarding frequency of motion in real world situations [1,9,10–14] indicate that exposure to low frequencies between 0.1 Hz and 1.0 Hz can be sickening.

Consistent with the hypothesis that varying amplitude of latency would be associated with increased sickness, participants experienced a higher level of SS and MS when exposed to a varying amplitude of latency as opposed to a fixed amplitude of latency. No prior research exists regarding the relationship between amplitude of latency and SS. Wu et al. [8] indicated that head tracking sensors produce a varying latency due to sensor tracking error, which helps explain why previous studies utilizing head tracked HMD systems [3–5] found a significant relationship between added latency and SS while studies not using a head tracked HMD system [6,7] failed to find a relationship between the two. It is likely that researchers using head tracked HMD systems have inadvertently exposed participants to varying latency. Hence, the current findings point to varying latency as an important variable in the genesis of HMD induced SS.

Like Moss and Muth [7], the current study was unable to support the hypothesis that added constant latency alone would be associated with a higher level of SS. Multiple studies [3–5] have found that added constant latency yields higher levels of sickness, but these have all involved a head-tracked system. Studies that have sought to isolate the effect of added latency have been unable to confirm the added latency effect [7]. Hence, as stated earlier, it is possible that the confound of unintentional frequency and amplitude of latency manipulations in head tracked HMD systems could potentially be the reason for findings that support a significant relationship between SS and added latency in head tracked HMD systems.

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

A repeated-measures ANOVA determined that time participating in the experimental task while wearing the HMD increased SS. Higher levels of SS were experienced by participants the longer they were in the HMD. These findings were similar to those found

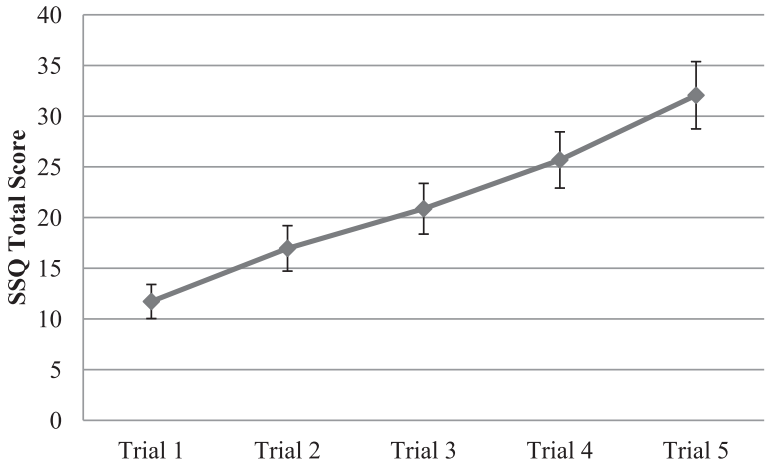

Fig. 6. Average SSQ total scores by trial with standard error bars.

in Moss and Muth [7]. These findings excluded participants who dropped-out prior to completion of the experimental trials, which means that participants were not equally distributed across trials.

4.1. Conclusions and future research

The use of HMDs will continue and the experience of SS in HMD VEs will continue to cause user problems unless influencing factors are completely understood and mitigated to the highest possible extent. The current study offers insight into the experience of SS while using an HMD. This study supports findings by Moss and Muth [7] that the relationship between constant latency and the experience of SS have not previously been fully understood. Previous findings by Wu et al. [8] indicated that in systems utilizing head trackers that varying amplitude and frequency of latency are present. This may explain why previous research using true HMD VEs [3–5] have found a relationship between added latency and SS while studies using image capture from a high speed camera [7] have not observed the same relationship. Findings from the current study revealed a significant relationship between amplitude of latency and SS as well as a potentially significant relationship between frequency of latency and SS. Future research should be performed to separately examine the effects of frequency and amplitude of latency over time and their interaction on the experience of SS.

The findings from this study indicate previous research regarding the relationship between latency and SS using HMDs with head trackers should be reviewed critically and carefully because of factors that may not have been controlled (i.e., the variations in frequency and amplitude of latency over time). Additionally, future HMD system design efforts should be made to help minimize drift in sensor error. This sensor error causes apparent fluctuations in amplitude and frequency of latency which according to the current research, have been linking to the users' experience of SS symptoms. An effort to minimize these elements in the design process may help to minimize the experience of SS.

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References

[1] J.F. O'Hanlon, M.E. McCauley, Motion sickness incidence as a function of the frequency and acceleration of vertical sinusoidal motion, Aviat. Space Environ. Med. 45 (1974) 366–369.
[2] R.M. Wildzunas, T.L. Barron, R.W. Wiley, Visual display delay effects on pilot performance, Aviat. Space Environ. Med. 67 (1996) 214–221.
[3] P. DiZio, J. Lackner, Circumventing side effects of immersive virtual environments, in: M.J. Smith, G. Salvendy, R.J. Koubek (Eds.), Advances in Human Factors/Ergonomics: Design of Computing Systems, vol. 21, Elsevier, Amsterdam, 1997, pp. 893–896.
[4] S. Jennings, G. Craig, L.D. Reid, R.V. Kruk, The effect of visual system time delay on helicopter control, in: Proc. of the IEA 2000/HFES 2000 Congr. vol. 3, 2000, pp. 69–72.
[5] S. Jennings, L.D. Reid, G. Craig, R.V. Kruk, Time delays in visually coupled systems during flight test and simulation, J. Aircr. 41 (2004) 1327–1335.
[6] M.H. Draper, E.S. Viirre, T.A. Furness, V.J. Gawron, Effects of image scale and system time delay on simulator sickness within head-couples virtual environments, Hum. Factors 43 (2001) 129–146.
[7] J.D. Moss, E.R. Muth, Characteristics of head-mounted displays and their effects on simulator sickness, Hum. Factors 53 (2011) 308–319.
[8] W. Wu, Y. Dong, A. Hoover, Measuring digital system latency from sensing to actuation at continuous 1 ms resolution, Presen.: Teleoperat. Virt. Environ. 22 (2013) 20–35.
[9] J.F. Golding, H.M. Markey, Effect of frequency of horizontal linear oscillation on motion sickness and somatogravic illusion, Aviat. Space Environ. Med. 67 (1996) 121–126.
[10] J.F. Golding, M.I. Finch, J.R.R. Stott, Frequency effect of 0.35–1.0 Hz horizontal translational oscillation on motion sickness and the somatogravic illusion, Aviat. Space Environ. Med. 68 (1997) 396–402.
[11] J.F. Golding, A.G. Mueller, M.A. Gresty, A motion sickness maximum around the 0.2 Hz frequency range of horizontal translational oscillation, Aviat. Space Environ. Med. 72 (2001) 188–192.
[12] S.J. Alexander, M. Cotzin, J.B. Klee, G.R. Wendt, Studies of motion sickness: XVI. The effects upon sickness rates of waves of various frequencies but identical acceleration, J. Exp. Psychol. 37 (1947) 440–448.
[13] A. Lawther, M.J. Griffin, Motion sickness and motion characteristics of vessels at sea, Ergonomics 31 (1988) 1373–1394.
[14] H.BL. Duh, D.E. Parker, J.O. Philips, T.A. Furness, "Conflicted" motion cues to the visual and vestibular self-motion systems around 0.06 Hz evoke simulator sickness, Hum. Factors 46 (2004) 142–153.
[15] R.S. Kennedy, N.E. Lane, K.S. Berbaum, M.G. Lilienthal, Simulator sickness questionnaire: a new method of quantifying simulator sickness, Int. J. Aviat. Psychol. 3 (1993) 203–220.
[16] P.J. Gianaros, E.R. Muth, J.T. Mordkoff, M.E. Levine, R.M. Stern, A questionnaire for the assessment of multiple dimensions of motion sickness, Aviat. Space Environ. Med. 72 (2001) 115–119.
[17] J.D. Moss, Characteristics of Head Mounted Displays and their Effects on Simulator Sickness (Doctoral Dissertation), 2008. <http://etd.lib.clemson.edu/documents/1211390564/umi-clemson-1649.pdf>.

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