The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects

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Dedication

This document is dedicated to my family. For nearly a decade Erin Lynn Munafo gave unconditional support and kindness that made this dissertation possible. May this dissertation serve as inspiration for our children.

Acknowledgements

This document is a labor of love and spite. It was through the many opportunities given to me that I completed this marathon. Thank you to Nikita Kuznetsov, Michael Riley, Kevin Shockley, and all of the fantastic people at the University of Cincinnati for helping me start my journey. A special thank you to Tom Stoffregen for the countless opportunities, moments of support, and for an unforgettable wedding night. Thank you to Michael Wade and Jeurgen Konczak for their support. Finally, thank you to Frank Koslucher, John Gaspar, and David Lee.

And to the person who told me on the evening before I left for Minneapolis that I should not bother because I would fail out anyway; may this document forever be the sun in your eyes.

Abstract

Anecdotal reports suggest that motion sickness may occur among users of contemporary, consumer-oriented head-mounted display systems, and that women may be at greater risk. I evaluated the nauseogenic properties of one such system, the *Oculus Rift*. The head-mounted unit included motion sensors that were sensitive to users' head movements, such that head movements could be used as control inputs to the device. In two experiments, seated participants played one of two virtual reality games for up to 15 minutes. In Experiment 1, 22% of participants reported motion sickness, and the difference in incidence between men and women was not significant. In Experiment 2, motion sickness was reported by 56% of participants, and incidence among women (77.78%) was significantly greater than among men (33.33%). Before participants were exposed to the head-mounted display system, I recorded their standing body sway during the performance of simple visual tasks. In both experiments, patterns of pre-exposure body sway differed between participants who (later) reported motion sickness and those who did not. In Experiment 2, sex differences in susceptibility to motion sickness were preceded by sex differences in body sway. These postural effects confirm a prediction of the postural instability theory of motion sickness. The results indicate that users of contemporary head-mounted display systems are at significant risk of motion sickness, and that in relation to motion sickness these systems may be sexist in their effects.

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Motion sickness is no longer confined to travel; it is increasingly common among users of interactive technologies, such as console video games (Stoffregen, Faugloire, Yoshida, Flanagan, & Merhi, 2008), and tablet computers (Stoffregen, Chen, & Koslucher, 2014). Motion sickness also has been reported among users of head-mounted display systems (e.g., boyd, 2014; Lewis, 2015). For early iterations of this technology, the anecdotal reports have been confirmed in controlled laboratory research (Merhi, Faugloire, Flanagan, & Stoffregen, 2007). Recently, a new generation of head-mounted display systems has gained widespread interest. These systems include improvements in display optics, such as spatial resolution. Perhaps more important, the current generation of head-mounted displays is notable for improvements in the sensing of user movement, and for the use of this information as control inputs for the display in real time. In contemporary systems, turning of the head and body yield realistic changes in visual display content: It is possible to "look around", "turn around", and even "walk around" within a fully immersive virtual environment. Examples include systems developed by Oculus (Oculus Rift), Samsung (Samsung Gear VR), and Google (Google cardboard).

Current head-mounted display systems are remarkable technological achievements, and they commonly give rise to subjective experiences of immersion that are very vivid. In this sense, these new systems are highly successful. Unfortunately, the user experience is not uniformly positive. Anecdotal reports make clear that a significant proportion of users rapidly transition from a pleasurable sense of immersion to a highly aversive sense of discomfort, disorientation, and nausea (e.g., boyd, 2014; Lewis, 2015). Despite intensive efforts on the part of manufacturers the problem has persisted, and has been acknowledged as the principal limitation on the widespread use of these systems (e.g., Lang, 2016). As yet, scientists have conducted few controlled, experimental studies on the nauseogenic properties of head-mounted interactive technologies (e.g., Draper, Virre, Furness, & Gawron, 2001; Merhi et al., 2007). Earlier generations of head mounted display systems were not widely accepted by consumers. By contrast, contemporary head mounted display systems have received widespread, sustained attention in the general media, and have been the subject of intense interest among consumers. For this reason, there is an urgent need for rigorous, experimental research that can evaluate the widespread anecdotal reports.

Console video games, tablet computers, head-mounted displays, and other interactive technologies differ from vehicles in that they do not include inertial displacement. Vehicles move relative to the Earth, but virtual environments typically do not. For this reason, nausea associated with contemporary interactive technologies is understood as an instance of visually induced motion sickness (e.g., Kennedy, Drexler, & Kennedy, 2010).

In both anecdotal reports and controlled research, motion sickness tends to be more common among women than among men. Perhaps the classic example is seasickness, where women are more susceptible than men by a ratio of approximately 5:3 (Lawther & Griffin, 1988). Researchers have begun to evaluate the possibility that sex differences may extend to visually induced motion sickness. Studies that have exposed participants to rotational visual motion stimuli in a spinning drum have found no sex differences (Klosterhalfen et al., 2006). By contrast, when Koslucher, Haaland, Malsch, Webler, and Stoffregen (2015) exposed participants to linear oscillating visual motion stimuli in a moving room, they found that the ratio of motion sickness incidence for women versus men was greater than 4:1. This result suggests that sex differences in susceptibility may be related to linear components of imposed motion, an hypothesis that is compatible with the finding that seasickness is related to vertical ship motion (known as *heave*), more strongly than to the angular components of ship motion (Lawther & Griffin, 1986).

Allen, Hanley, Rokers, and Green (2016, cf. McConville & Milosevic, 2014; Read & Bohr, 2014) exposed standing participants to three-dimensional stereoscopic films presented via an early version of the Oculus head-mounted display system (the Oculus DK-1). They reported that females were more likely than males to experience discomfort. However, Allen et al. did not directly assess either the incidence or severity of motion sickness. Instead, they compared participants who viewed the entire 20-minute presentation versus viewers who chose to discontinue early. This distinction between "quitters" and "survivors" is only weakly related to actual motion sickness incidence. Virtual reality technologies give rise to a wide range of subjective side effects, not all of which are associated with motion sickness (e.g., Stanney et al., 1998). In some cases, participants have chosen to discontinue exposure to a virtual environment but have expressly denied being motion sick (Koslucher et al., 2015; Merhi, Faugloire, Flanagan, & Stoffregen, 2007; Stoffregen, Faugloire, Yoshida, Flanagan, & Merhi, 2008). In addition, the fact that a participant completed a motion sickness protocol does not imply that the participant did not become sick. Motion sickness can develop after the completion of experimental protocols, either immediately afterward (e.g., Merhi et al., 2007; Stoffregen, Yoshida, Villard, Scibora, & Bardy, 2010) or up to 12 hours later (e.g., Kennedy & Lilienthal, 1994; Stoffregen, 1985). For these reasons, the study of Allen et al. cannot be interpreted as a study of motion sickness.

A defining feature of head-mounted display systems is that visual motion is controlled by the user. Control of motion is an important factor in the etiology of motion sickness in vehicles (e.g., Rolnick & Lubow, 1991) but also in virtual environments (e.g., Chen, Dong, Chen, & Stoffregen, 2012; Dong, Yoshida, & Stoffregen, 2011; Stoffregen et al., 2014). Research on sex differences in visually induced motion sickness has not included comparisons between men and women during exposure to "closed loop" control of visual imagery (Allen et al., 2016; Klosterhalfen et al., 2006; Koslucher et al., 2015). I asked whether contemporary head-mounted interactive systems would give rise to motion sickness when participants' head movements altered display content in real time. In addition, I asked whether there would be sex differences in the incidence and severity of motion sickness. Our focus was on the Oculus DK-2 head-mounted display system, commonly known as the *Oculus Rift*.

Visually induced motion sickness is preceded by patterns of postural activity (including the spatial magnitude and temporal dynamics of body sway) that differ between individuals who (later) report motion sickness and those who do not. Differences have been observed in standing body sway (e.g., Bonnet, Faugloire, Riley, Bardy, & Stoffregen, 2006; Stoffregen & Smart, 1998) and in motion of the head and torso while seated (e.g., Chen, Dong et al., 2012; Dong et al., 2011; Stoffregen, Hettinger, Haas, Roe, & Smart, 2000; Stoffregen et al., 2014). Generalized assessments of postural sway during unperturbed stance have identified sex differences in the quantitative kinematics of sway (e.g., Chiari, Rocchi & Cappello, 2002; Era et al. 2006). Taken together, these findings suggest it might be the case that sex differences in the control of postural activity are causally related to sex differences in susceptibility to motion sickness. This hypothesis is compatible with the postural instability theory of motion sickness (Riccio & Stoffregen, 1991), which predicts that postural sway will differ between individuals that experience motion sickness and those who do not, and that those differences will exist prior to the onset of subjective symptoms of motion sickness. Koslucher, Haaland, and Stoffregen (2016) evaluated unperturbed standing body sway before participants were exposed to visual motion that induced motion sickness in some participants. They found that sex differences in the incidence of motion sickness were preceded by sex differences in sway (in a statistically significant 3-way interaction between sex, motion sickness incidence, and visual tasks). I predicted that similar effects would occur before participants were exposed to a contemporary head-mounted virtual reality system.

The present study

We asked whether the Oculus Rift could induce motion sickness in a laboratory setting when used as recommended, with publically available game applications. I predicted that the incidence and severity of motion sickness would differ between games, consistent with previous studies (e.g., Merhi, Faugloire, Flanagan, & Stoffregen, 2007), and that sickness would be more common among women than among men. Finally, I measured unperturbed standing body sway before participants were exposed to the Oculus Rift, and I predicted that body sway would differ between participants who (later) reported motion sickness and those who did not, as a function of sex. I separately evaluated the spatial magnitude and the temporal dynamics of postural sway.

Experiment 1

In Experiment 1, I asked whether motion sickness would occur when seated participants played a virtual reality game using the Oculus Rift headset. I also asked about possible sex differences in the incidence of motion sickness. In addition, before participants played the game I measured their unperturbed body sway during performance of two different visual tasks. I predicted that unperturbed standing body sway would differ between participants who (later) reported motion sickness and those who did not. Finally, I predicted that, if there was a sex difference in motion sickness incidence, then this would be reflected in the postural sway data as a statistically significant interaction including motion sickness status and sex.

Method

Participants

The participants were 36 undergraduates (mean age = 20.72 years, SD = 0.85 years) from the University of Minnesota, comprising 18 men and 18 women.

The experimental protocol was approved, in advance, by the University of Minnesota IRB.

Apparatus

We monitored standing body sway using a force plate (Accusway, AMTI, Watertown, MA). I recorded the position of the center of pressure in the anterior-posterior (AP) and mediolateral (ML) axes, at 50 Hz.

We used the 2nd version of the Oculus development kit, known as the DK-2, or the *Oculus Rift.* The device comprised a lightweight (0.44 kg) headset that completely covered the field of view. The headset included separate displays for each eye, each with

960 × 1080 resolution, yielding a 100° horizontal field of view. A lens located in front of each display rendered display content at optical infinity.

Participants used the Oculus Rift while seated on a stool. The stool had no back, and was built in such a way that the participant could rotate freely; that is, they could rotate around the vertical axis of the stool. So long as they remained seated on the stool, they were permitted to move in any way that they wished.

Procedure

Each participant gave informed consent and was informed they could discontinue at any time without penalty. Following the informed consent procedure, completed the Simulator Sickness Questionnaire, or SSQ (Kennedy, Lane, Berbaum, & Lilienthal, 1993), which allowed us to assess the initial level of symptoms (SSQ-1). Following Regan and Price (1994), I used these pre-exposure SSQ data to establish a baseline against which later SSQ data could be compared. The SSQ comprises 16 symptoms, each of which is rated on a 4-point scale (not at all, mild, moderate, severe). Participants also responded to a forced-choice, yes/no question, *"Are you motion sick?"* Participants were instructed (both verbally and on the consent form) to discontinue the experiment immediately if they experienced any motion sickness symptoms, however mild. Participants next reported their gaming habits. I asked whether participants currently played video games and, if so, how many hours per week.

After completing SSQ-1 and reporting their gaming habits, participants removed their shoes and were measured for height and weight, after which they stood on the force plate. The force plate was located one meter from a wall. Participants stood on marked lines on the plate such that their heels were 17 cm apart with an angle of 10° between the feet. While standing on the force plate, each participant completed three trials in an Inspection task and three in a Search task. Visual targets were identical to those used by Stoffregen, Pagulayan et al. (2000). Targets consisted of sheets of white paper 13.5 cm × 17 cm, mounted on rigid cardboard. Targets for the Inspection and Search tasks were 1.0 m in front of the heels, affixed to a white wall and adjusted to each participant's eye height. In the inspection task, the target was a blank sheet of white paper. There was not a single fixation point: Participants were instructed to keep their gaze within the boundary of the target. In the Search task, the target was a block of English text, comprising 14 lines of text printed in a 12-point sans serif font, which was affixed to an otherwise blank card. In the Search task, the participant was asked to count the number of times the letter, *m*, appeared in the block of text. At the end of each Search trial, the participant reported the number of letters counted and their position in the text at the end of the trial. Each trial was 60 s in duration. The Inspection and Search tasks were presented in alternating order. Odd-numbered participants began with the Search task, while even-numbered participants began with the Inspection task.

After the standing balance trials, participants sat on the stool and donned the Oculus Rift headset. The Experimenter explained the controls, but participants were not given any practice with the system. Participants were instructed to discontinue participation immediately if they experienced any symptoms of motion sickness, however mild. They played *Balancer Rift* (share.oculus.com). The goal of this game was to roll a virtual marble through a virtual maze on a board that could be tilted using head movements. Participants were informed that the Oculus Rift used head movements to control the display, and they would need to use head movements to solve the puzzle.

There was no translational motion: The game consisted solely of tilting the maze through head motion. If the participant did not complete the game in 2 minutes the software automatically reset, and the game started over. Participants were instructed to complete the game as many times as possible until 15 minutes elapsed or they discontinued, whichever came first. After the conclusion of game play participants again answered the forced-choice question, *Are you motion sick?*, after which they completed the SSQ a second time (SSQ-2). Participants who stated that they were not motion sick at SSQ-2 were given a printed copy of the SSQ (SSQ-3) that included the forced-choice question, *Are you motion sick?,* which they were instructed to complete if they began to feel motion sick at any time during the following 24 hours or, if they did not experience motion sickness, after 24 hours.

Data analysis

We separately assessed the incidence and severity of motion sickness (e.g., Dong et al., 2011; Koslucher et al., 2015; Merhi et al., 2007; Stoffregen et al., 2008; Stoffregen & Smart, 1998; Stoffregen et al., 2010). Researchers often do not distinguish between the incidence of motion sickness and the severity of motion sickness symptoms. Severity measures (e.g., symptom ratings) are continuous, and this feature can sometimes be an advantage. Our study was based on the postural instability theory of motion sickness (Riccio & Stoffregen, 1991), which makes predictions about differences in postural activity between persons who are experiencing motion sickness and those who are not. Because the predictions are formulated in this way, testing of the predictions requires that I adopt a dichotomous sick/well classification, rather than a graded scale. For this reason, I assessed motion sickness incidence by asking participants to make forced choice, yes/no statements about whether they were motion sick. I assigned participants to the Well and Sick groups based solely upon their responses to the forced-choice question, *Are you motion sick*? Participants answering *yes* were assigned to the Sick group. All others were assigned to the Well group. Because participants could discontinue at any time for any reason, there was no motivation to give false reports of motion sickness as a means to discontinue participation. For this reason, I accepted at face value participants' statements that they were motion sick.

We evaluated the severity of motion sickness symptoms using the SSQ. To summarize SSQ responses, I used the total severity score, which I computed in the recommended manner (Kennedy et al., 1993). SSQ scores are not normally distributed, and for this reason in analyzing SSQ data I used non-parametric statistics.

We separately evaluated the spatial magnitude and multifractality of center of pressure positions. I evaluated the spatial magnitude of postural activity in terms of positional variability, which I defined operationally as the standard deviation of center of pressure positions. I evaluated the multifractality of postural activity using multifractal detrended fluctuation analysis, MF-DFA (e.g., Ihlen, Skjaeret, & Vereijken, 2013; Munafo, Curry, Wade, & Stoffregen, 2016). MF-DFA is an extension of more traditional detrended fluctuation analysis, or DFA (Lin et al., 2008). Traditional DFA assumes that fluctuations in a time series are homogeneous (Ihlen & Vereijken 2010). Multifractal fluctuations are interdependent and heterogeneous. The range of the singularity exponent, $h(q)$, indicates the heterogeneous nature of multifractal fluctuations (Ihlen, 2012). The width of this range can be used as an index of the degree (or amount) of multifractality in a time series. The range of $h(q)$ values is known as the *singularity spectrum*, or simply the *spectrum*. The wider the multifractal spectrum, the more multifractal is the movement (Kelty-Stephen et al., 2013). I conducted inferential statistics on the width of the singularity spectrum for each trial. I conducted MF-DFA using open source code for MATLAB (MFDFA1; Ihlen, 2012). I selected a minimum scaling range of 16 data points with 19 evenly spaced increasing segment sizes to a maximum of the length of the time series. This range was the same for each time series. I conducted separate ANOVAs on positional variability and the width of the multifractal spectrum. There were 3000 data points in each time series.

Results

Motion sickness incidence and severity. The overall incidence of motion sickness was 22% (8/36). Two of 18 men (11.11%) and six of 18 women (44.44%) stated that they were motion sick. Using a 2 × 2 contingency table, the difference in incidence between women and men was not significant, χ^2 (1) = 2.57, p = .11. Six participants discontinued early (one man and 5 women), with a mean time of discontinuation of 6.24 minutes. Each of these six participants reported motion sickness on SSQ-2. Two participants completed the 15-minute exposure before reporting motion sickness, also reporting motion sickness on SSQ-2. No participants reported sickness on SSQ-3.

SSQ total severity scores are summarized in Figure 1. At SSQ-1, total severity scores did not differ between the sexes, U = 139, p = .48, or between the well and sick groups U = 92.5, p = .47. Following game play (at SSQ-2), scores did not differ between women and men, U = 133.5, p = .37, but did differ between the well group and the sick group, U = 31.5, p = .001.

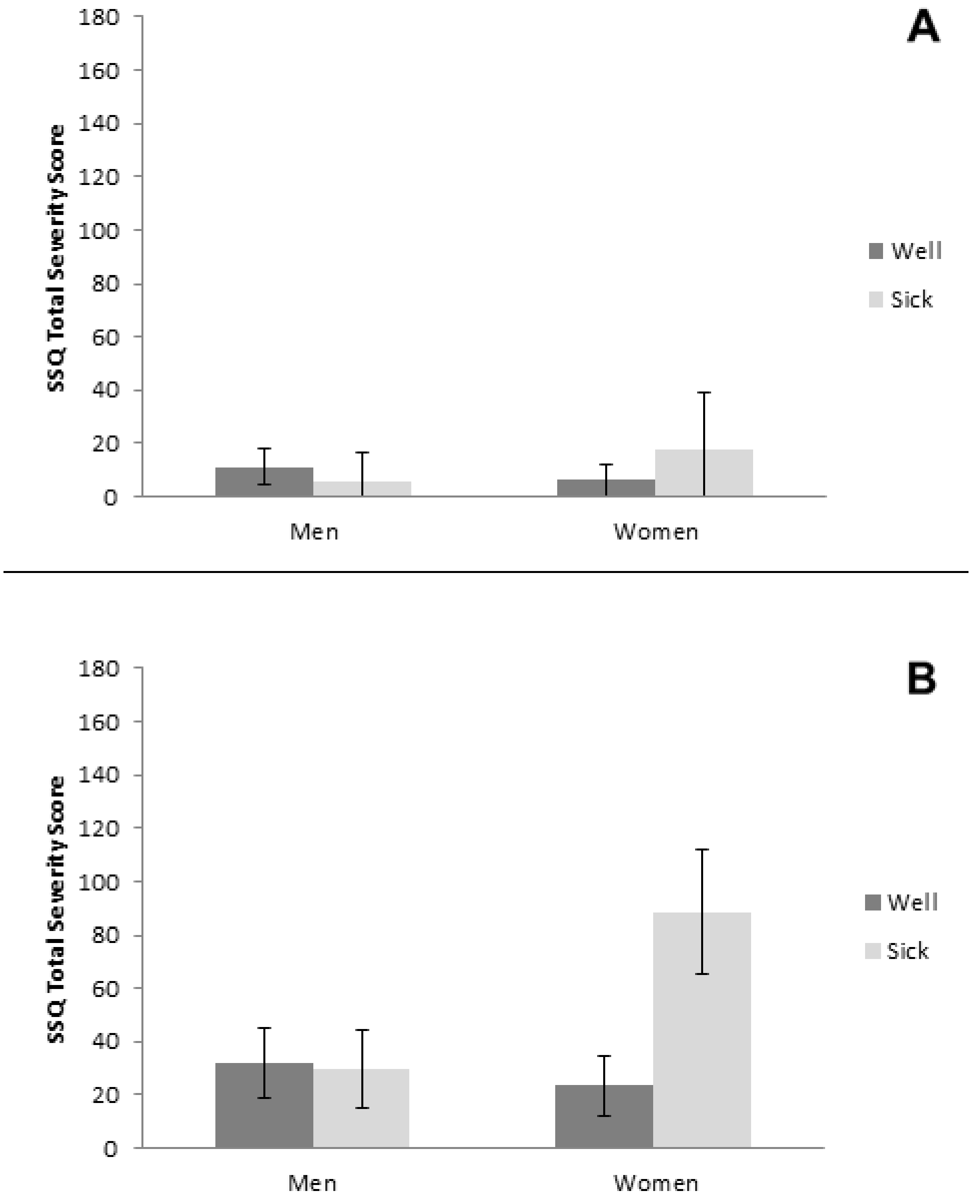


Figure 1. Subjective symptoms (SSQ Total Severity Score) in Experiment 1. A. Before exposure to the Oculus Rift. B. After exposure to the Oculus Rift. The error bars represent the 95% confidence interval of the mean.

Search task performance. There was not a formal measure of performance for the Inspection task. Following previous studies (e.g., Koslucher et al., 2016; Stoffregen et al., 2000), I assumed that participants were able to maintain their gaze within the borders of the target. For the Search task, I evaluated performance in terms of the number of target letters counted as a percentage of the total number of target letters in the stimulus text. Overall, participants counted 78.92% of target letters. I used independent sample *t*-tests to evaluate differences in task performance between the sexes, and between sickness groups. Task performance did not differ between men (M = 76.71% SD = 17.58%) and women (M = 81.12% SD = 10.57%), $t(34) = .91$, $p = .37$, or between the Well (M = 79.34% SD = 15.91%) and Sick (M = 77.43% SD = 8.19%) groups, $t(34) = .32$, $p = .17$.

Postural sway. For two participants (one male, one female) the positional variability data for one or more conditions were three or more standard deviations above the group mean for the same condition(s). For this reason, I excluded these two participants from the analysis of positional variability.

For the positional variability of the center of pressure, the main effect of axis was significant, $F(1,30) = 88.08$, $p < .001$, partial $\eta^2 = .75$. Positional variability was greater in the AP axis (mean = 0.40 cm, SE = .03 cm) than in the ML axis (mean = 0.19 cm, SE = .01 cm). There were no other significant effects in positional variability.

For the width of the multifractal spectrum, the main effect of Axis was significant, $F(1,31) = 4.27$, $p = .047$, partial $\eta^2 = 0.12$. Spectrum width was greater in the AP axis (mean = 0.37, SE = 0.01) than in the ML axis (mean = 0.35, SE = 0.02). In addition, the Visual Task × Sickness Groups interaction was significant, $F(1,32) = 4.80$, $p = .036$, partial $\eta^2 = .134$. As can be seen in Figure 2, the relation between postural responses to the two tasks differed qualitatively between participants in the Well and Sick groups. There were no other significant effects.

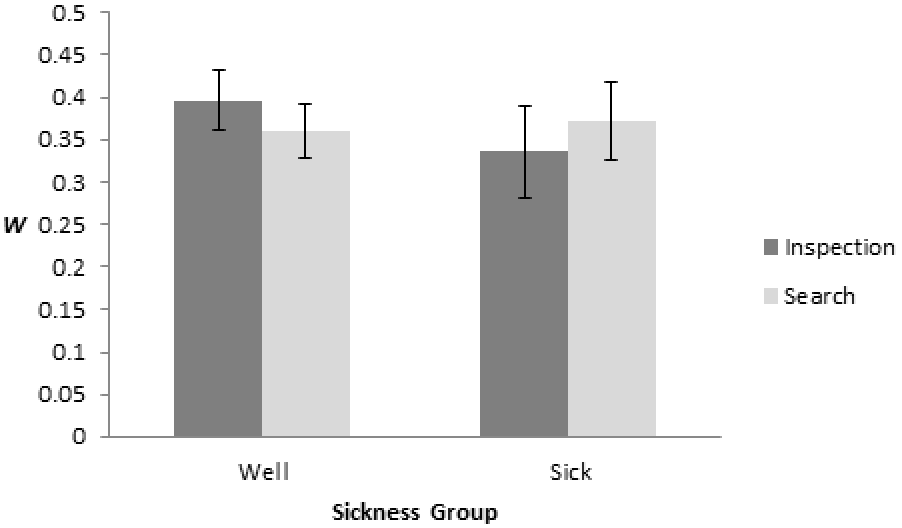


Figure 2. Experiment 1. Width of the range of singularity exponents of the multifractal spectrum, *W*, for standing postural sway before exposure to the Oculus Rift. The figure illustrates the statistically significant interaction between Task (Inspection vs. Search) and Sickness Groups (Well vs. Sick). The error bars represent the 95% confidence interval of the mean.

Discussion

Seated participants wore the Oculus Rift head-mounted display system, and played a game in which head movements were used as game inputs. After playing the game for a maximum of 15 minutes, motion sickness was reported by 22% of participants. For a mass market product, this level of motion sickness incidence could be considered to be high, especially given the brief exposure time. As noted earlier, the persistence of motion sickness among users has been identified as a major limitation of the current generation of head-mounted display systems (Lang, 2016). At the same time, the 22% incidence observed in Experiment 1 is low relative to rates of motion sickness incidence reported in previous experimental studies. Merhi et al. (2007) evaluated motion sickness among users of an earlier-generation head-mounted display system. Among seated participants, the minimum incidence of motion sickness observed in their study was 59%. However, it is important to point out that exposure to the head-mounted display system in earlier studies was far longer than in the current study. For example, in Merhi et al., participants used a head-mounted display system for up to 50 minutes, while in Draper et al. (2001), participants used a head-mounted display for 30 minutes. In the present study, it seems reasonable to suppose that the overall incidence of motion sickness would have been higher if participants used the device for 30 or 50 minutes. Before using the Oculus Rift, participants performed the Inspection and Search tasks while standing. Search task performance did not differ between the sexes, or between the Well and Sick groups. These results differ from Koslucher, Haaland, and Stoffregen (2016), who found that men counted a greater percentage of target letters than women. The Search task used in the present study was identical to that used by Koslucher et al. The difference in results may arise from the fact that the sample size used by Koslucher et al., was more than three times larger than in the present study.

During performance of the Inspection and Search tasks, the positional variability of the center of pressure was greater in the AP axis than in the ML axis, replicating classical effects (e.g., Balasubramaniam, Riley, & Turvey, 2000; Koslucher et al., 2014). In monitoring postural activity, our principal aim was to determine whether motion sickness was preceded by distinctive patterns of body sway during unperturbed stance.

The spatial magnitude of sway, as indexed by the positional variability of the center of pressure, did not differ between participants who later reported motion sickness and those who did not. However, the multifractality of sway did differ significantly between participants who later became sick and those who did not, as mediated by our variation in visual tasks performed during stance (Figure 2). Previous researchers have not evaluated the multifractality of unperturbed body sway in relation to subsequent motion sickness (e.g., Koslucher et al.; Stoffregen et al., 2010). Accordingly, the finding illustrated in Figure 2 is novel. The effect confirms the prediction of the postural instability theory of motion sickness (Riccio & Stoffregen, 1991) that postural activity should differ between individuals who experience motion sickness and those who do not, and that such differences should precede the onset of subjective symptoms of motion sickness. In Experiment 1, differences in postural activity existed in unperturbed stance before participants were exposed to any visual motion stimuli (cf. Stoffregen et al., 2013; Stoffregen et al., 2010; Stoffregen & Smart, 1998).

Despite the fact that the incidence of motion sickness was three times greater in women than in men, the sex difference was not statistically significant. This result could indicate that there are no sex differences in motion sickness among users of head-mounted display systems. An alternative hypothesis is that in Experiment 1 actual sex differences were masked by the low overall incidence of motion sickness. Overall incidence might be higher, and sex differences in incidence might be significant if the Oculus Rift were used with a different game. To evaluate this hypothesis was the primary purpose of Experiment 2.

Experiment 2

When video games have been presented on head-mounted displays the incidence and severity of motion sickness has varied across different games (Merhi et al., 2007). In Experiment 2, I asked whether this was true also for games presented through the Oculus Rift. In addition, I asked whether sex differences in motion sickness might vary across different games, and whether any such differences might be related to postural precursors of motion sickness.

Method

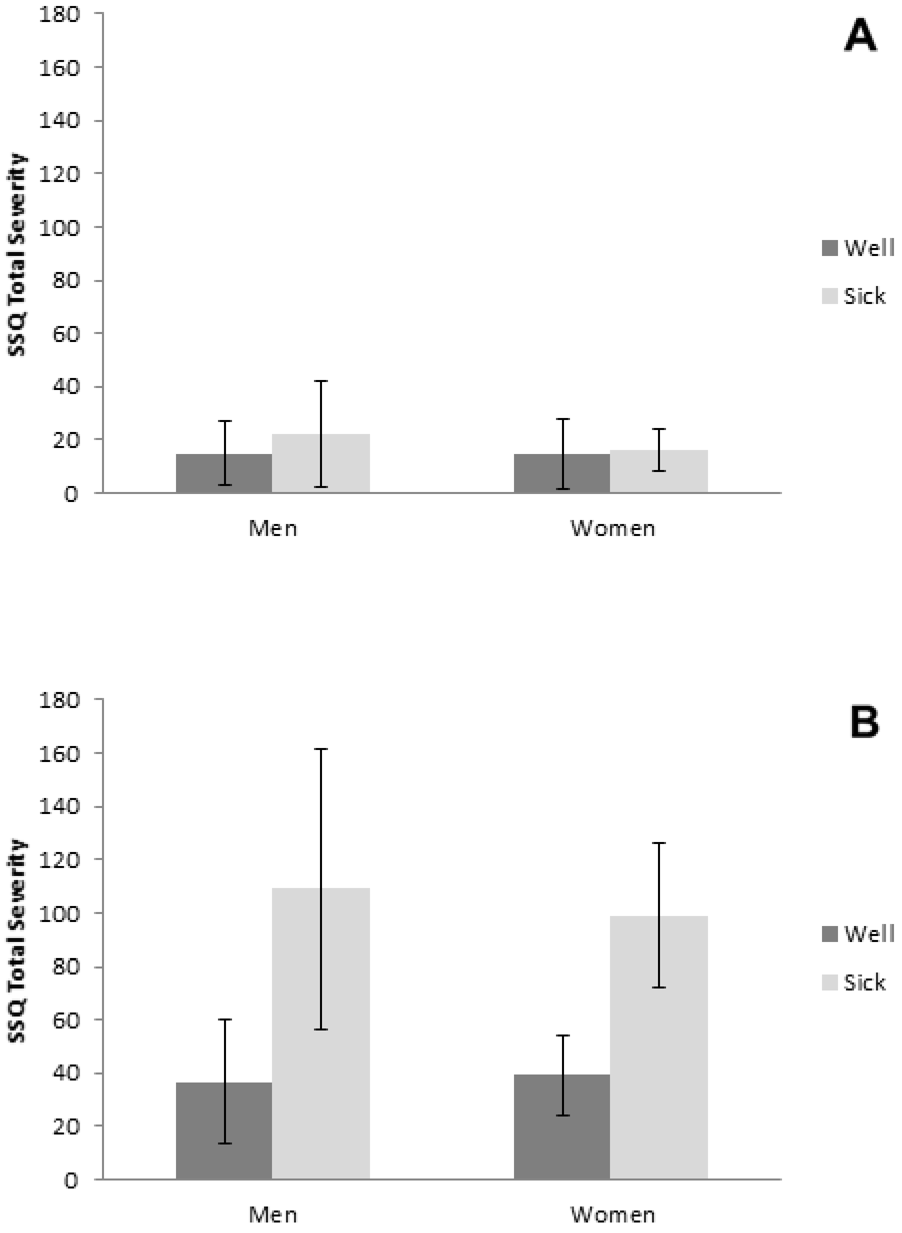
The method for Experiment 2 was the same as for Experiment 1. The sole difference was that in Experiment 2 participants played a different game, *Affected* (games.softpedia.com). In this first-person game, participants navigated an environment of hallways and rooms. The goal was to reach a designated end point in the virtual layout. The translational component of navigation was controlled via a hand held controller. Rotational components of navigation were controlled using head movements. Participants used head movements to control the direction of virtual gaze: Rotation of the head to the left (or right) caused virtual gaze to rotate to the left (or right), and rotation of the head up or down caused virtual gaze to rotate up or down, respectively. Participants were instructed to repeat the navigation task if they finished it before 15 minutes elapsed. Participants were instructed to discontinue participation immediately if they experienced any symptoms of motion sickness, however mild.

Results

Motion sickness incidence and severity. The overall incidence of motion sickness was 56% (20/36), which was greater than in Experiment 1 (22%), $\chi^2 = 8.42$, $p = .004$. Six men (33.33%) and fourteen women (77.78%) reported becoming motion sick. Using a 2 × 2 contingency table, the difference between the sexes was significant, χ^2 (1, n = 36) = 7.2, $p = .007$, indicating that women were more likely than men to state that they were motion sick. The overall ratio of sick women to sick men was 2.33:1.

Twenty participants completed the 15-minute exposure (12 men and 8 women). Of these, five (2 men and 3 women) reported motion sickness on SSQ-2, while three (1 man and 2 women) reported motion sickness at SSQ-3. Sixteen participants discontinued without completing the 15-minute exposure (6 men and 10 women). Due to an experimenter error, the time of discontinuation was not recorded for one of these participants. For the remaining 15 participants who discontinued, the mean exposure time was 7.06 minutes. Of these, 12 (3 men and 9 women) reported motion sickness (all at SSQ-2), while three participants (all male) stated that they were not motion sick (all three participants cited general discomfort as the reason for discontinuing). The proportion of participants who discontinued early (i.e., who did not complete the 15-minute exposure) and who stated that they were motion sick was greater in Experiment 2 (0.36) than in Experiment 1 (0.17), $\chi^2 = 4.00$, $p = .022$.

SSQ total severity scores are summarized in Figure 3. Before exposure to the Oculus Rift (SSQ-1), total severity scores did not differ between the sexes, $U = 152$, $p = .77$, or between the Well and Sick groups, $U = 139.5$, $p = .52$. Following game play (SSQ-2), scores were higher for the Sick group than for the Well group, $U = 52$, $p < .001$, but did not differ between women and men, $U = 114.5$, $p = .13$.

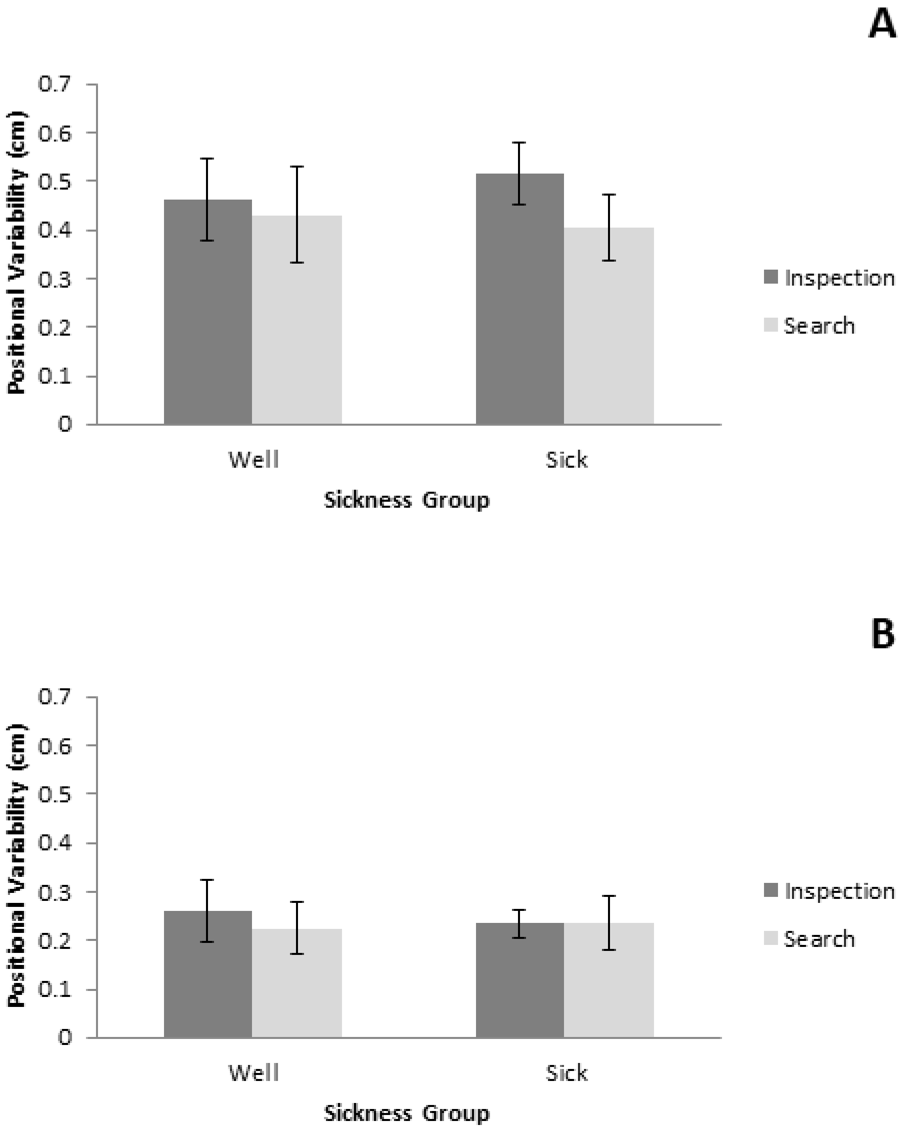


<u>Figure 3</u>. Subjective symptoms (SSQ Total Severity Score) for Experiment 2. A. Before exposure to the Oculus Rift. B. After exposure to the Oculus Rift. The error bars represent the 95% confidence interval of the mean.

Search task performance. Overall, participants counted 81.80% of target letters in the Search task. The difference between men (mean = 78.32%, SD = 14.88%) and women (mean = 85.29%, SD = 9.11%) was not significant, *t*(34) = 1.70, *p* = .092. Similarly, the difference between the Well group (mean = 81.60% SD = 6.84%) and the Sick group (mean = 82.00%, SD = 16.08%) was not significant, *t*(34) = -.086., *p* = .93.

Postural sway. For two participants (one male, one female) individual means for positional variability were three or more standard deviations above the group mean. Accordingly, these two participants were deleted from our analysis of postural activity (listwise deletion).

For positional variability of the center of pressure the main effect of Axis was significant, F(1,30) = 182.63, $p < .001$, $\eta^2 = 0.86$. Positional variability in the AP axis (mean = 0.48 cm, SE = .03 cm) was greater than in the ML axis (mean = 0.25, SE = .02). The Task × Axis × Sickness Groups interaction was significant, F(1,30) = 9.00, *p* = .005, $\eta^2 = 0.23$. As can be seen in Figure 4, effects of visual tasks and sickness status were concentrated in the AP axis. Additionally, the Task × Sickness Groups × Sex interaction was significant, F(1,30) = 5.27, *p* = .029, $\eta^2 = 0.15$. As shown in Figure 5, relations between visual tasks, and sickness groups different qualitatively as a function of sex.



<u>Figure 4</u>. Experiment 2. Positional variability of the center of pressure before exposure to the Oculus Rift, illustrating the statistically significant interaction between Task (Inspection vs. Search), Axis (AP vs. ML), and Sickness Groups (Well vs. Sick). A. AP axis. B. ML axis. The error bars represent the 95% confidence interval of the mean.

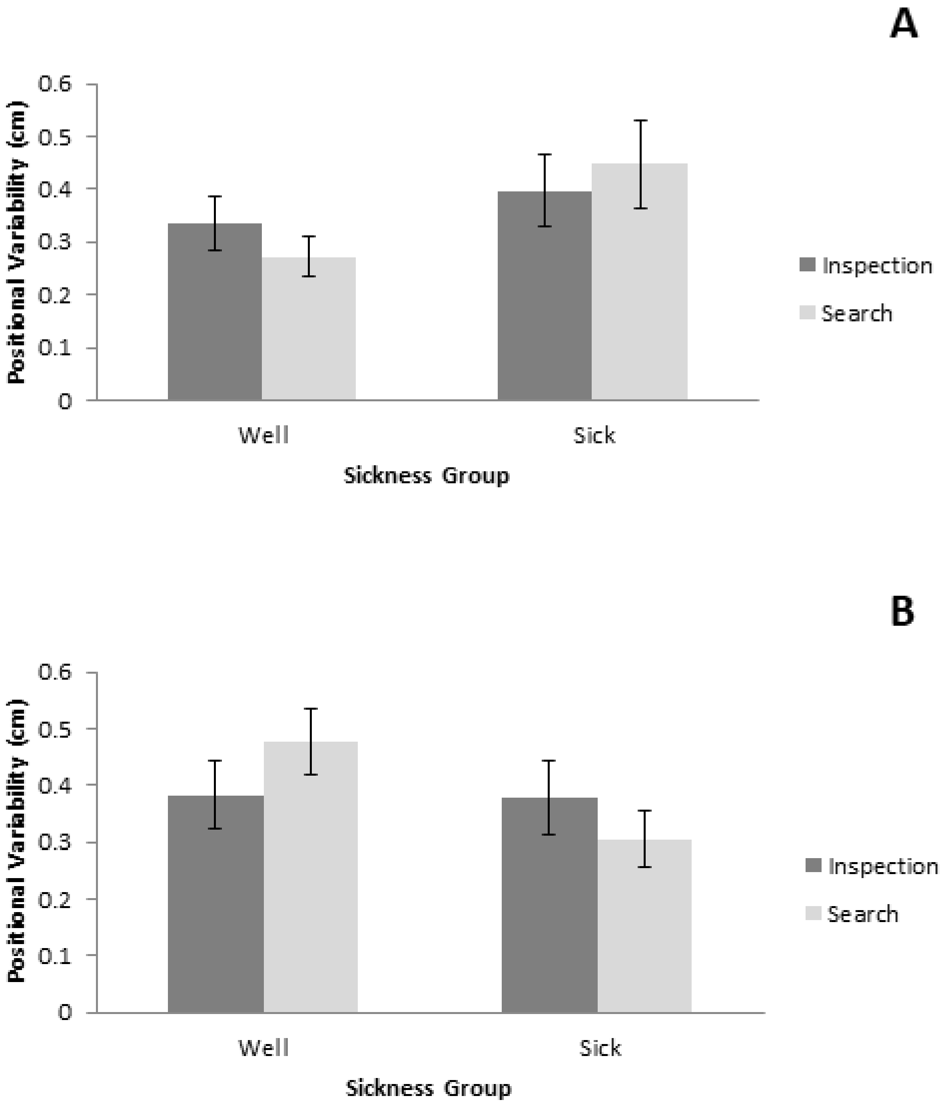


Figure 5. Experiment 2. Positional variability of the center of pressure during stance, before exposure to the Oculus Rift. The figure illustrates the statistically significant interaction between Task (Inspection vs. Search), Sickness Groups (Well vs. Sick), and Sex. A. Men. B. Women. The error bars are the 95% confidence interval of the mean.

For the width of the multifractal spectrum, the Task × Axis interaction was significant, F(1,32) = 5.86, *p* = .021, $\eta^2 = 0.16$. As can be seen in Figure 6, the relation between sway in the AP and ML axes differed qualitatively as a function of visual tasks.

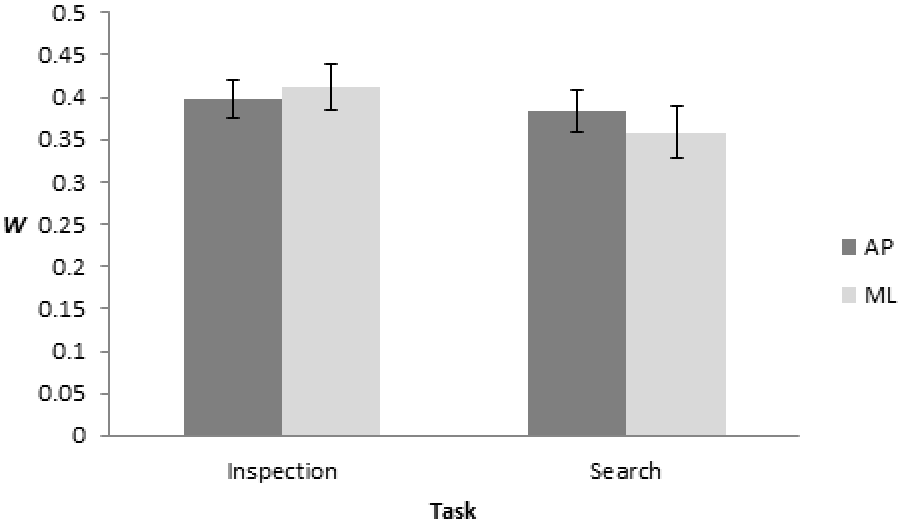


Figure 6. Experiment 2. Multifractality of COP sway, *W*, during stance, before exposure to the Oculus Rift, illustrating the statistically significant interaction between Task (Inspection vs. Search) and Axis (AP vs. ML). The error bars represent the 95% confidence interval of the mean.

Discussion

In Experiment 2, the Oculus Rift was again associated with motion sickness. It is remarkable that more than half of participants reported becoming motion sick after using the system for a maximum of 15 minutes. The overall incidence of motion sickness in Experiment 2 (56%) was greater than in Experiment 1 (22%). This result replicates game-based differences in incidence reported by Merhi et al. (2007), and confirms widespread anecdotal reports indicating that for a given hardware system the risk of motion sickness can be affected by variations in game content. In addition, the proportion of participants who completed the 15-minute exposure to the game was lower in Experiment 2 than in Experiment 1.

In Experiment 2, the incidence of motion sickness was greater among women than among men. For each male who reported sickness, 2.33 females reported sickness. This result confirms anecdotal reports suggesting that the risk of motion sickness arising from the use of head-mounted display systems can be greater for women than for men (e.g., boyd, 2014), and is consistent with the finding that women are more susceptible than men to motion sickness induced by linear oscillation of the illuminated environment (Koslucher et al., 2015), as well as with the fact that women are more susceptible than men to motion sickness, in general (e.g., Lawther & Griffin, 1986, 1988).

During unperturbed stance, the positional variability of the center of pressure was greater in the AP axis than in the ML axis, replicating Experiment 1. In addition, unperturbed postural activity was strongly influenced by our variation in visual tasks, as reflected in the fact that visual tasks was a factor in each of the statistically significant effects on postural sway (Figures 4-6). Before exposure to the head-mounted display system, postural sway differed between participants who later became sick and those who did not, as part of a 3-way interaction that included visual tasks and body axis (Figure 4). This result confirms a prediction of the postural instability theory of motion sickness (Riccio & Stoffregen, 1991).

Our analysis of the positional variability of the center of pressure also revealed a statistically significant 3-way interaction that included visual tasks, sickness groups, and sex (Figure 5). That is, the effects of the Inspection and Search tasks on postural activity differed between participants who later became motion sick and those who did not, as a function of sex. As can be seen in Figure 5, during performance of the Search task the patterns of postural activity that preceded motion sickness differed qualitatively between women and men. The same 3-way interaction was statistically significant when Koslucher, Haaland, and Stoffregen (2016) evaluated unperturbed postural activity measured (during performance of the same visual tasks) before participants were exposed to open-loop linear visual oscillation in a moving room. Across the two studies, the direction of effects in the 3-way interaction differed (compare Figure 5 of the present study with Figure 4 from Koslucher et al., 2016).

In Experiment 1, I found that motion sickness was preceded by distinctive patterns in the width of the multifractal spectrum (Figure 2). By contrast, in Experiment 2 postural multifractality was not related to subsequent motion sickness. Separately, Koslucher et al. (2014) found that the postural precursors of motion sickness differed as a function of whether participants wore weights attached to the thighs, or attached to the torso. Differences in the postural precursors of motion sickness between conditions and studies suggest that there may be subtle relationships between particular parameters of postural activity and the tendency for postural control to be destabilized by particular parameters of motion stimuli. For example, it may be that the patterns of postural sway that precede motion sickness when standing participants are exposed to open-loop linear visual oscillation (as in Koslucher, Haaland, & Stoffregen, 2016) are different from patterns of postural sway that precede motion sickness when seated participants are exposed to closed-loop visual motion in a head-mounted virtual environment (as in the present study). This question could be addressed by examining relations between postural sway and subsequent motion sickness across variations in situations, stimuli, and tasks, using a within-participants design.

General Discussion

In two experiments, I measured standing body sway while participants performed simple visual tasks, after which seated participants played one of two virtual reality games using the Oculus Rift system. After a maximum exposure of 15 minutes, each game led to motion sickness in some participants. The incidence of motion sickness differed significantly between games. In Experiment 2, the incidence of motion sickness was significantly greater among women than among men. In both experiments, the kinematics of unperturbed postural activity, measured before participants were exposed to the head-mounted display system, differed between participants who (later) reported motion sickness and those who did not, as mediated by our variation in visual tasks performed during stance. In addition, in Experiment 2, the visual task × sickness groups interaction was itself mediated by sex, consistent with the hypothesis that sex differences in the incidence of motion sickness are preceded by sex differences in postural activity. I discuss these results in turn.

The overall incidence of motion sickness

We confirmed that the Oculus Rift can induce motion sickness when used by seated participants in closed-loop mode, such that the contents of the visual display were continuously updated on the basis of head movements, and that sickness can be induced in 15 minutes or less. The fact that motion sickness was induced in such brief exposures testifies to the nauseogenic power of head-mounted display systems. By contrast, motion sickness associated with console video games typically occurs after 20-35 minutes of exposure (Chang et al., 2012; Stoffregen et al., 2008). Thus, it seems likely that with longer exposure time to a head-mounted display system the incidence of motion sickness would be greater.

Motion sickness incidence in Experiment 2 was greater than in Experiment 1, confirming that, for a given display system the risk of motion sickness differs between games (cf. Merhi et al., 2007). In the broader literature, it is well known that the risk of motion sickness varies across situations and settings, including variations in the nature of motion stimuli (e.g., Klosterhalfen et al. 2006; Koslucher et al., 2015). Perhaps the most widely appreciated example is the fact that among people traveling in physical or virtual vehicles motion sickness is less common among individuals who control the vehicle (e.g., drivers) and more common among individuals who do not (e.g., passengers; Dong et al., 2011; Rolnick & Lubow, 1991; cf. Stoffregen, Chen, & Koslucher, 2014).

Sex differences in motion sickness incidence

Motion sickness was more common among women than among men; in Experiment 2, this effect was statistically significant. This finding is consistent with studies in many domains (e.g., Koslucher et al., 2015; Lawther & Griffin, 1986, 1988), and with anecdotal reports about head-mounted display systems (e.g., boyd, 2014). Sex differences are of special relevance for consumer products in part due to their pervasive use. Motion sickness occurs among players of console video games (e.g., Stoffregen et al., 2008), among users of tablet computers (Stoffregen et al., 2014), and, anecdotally, among users of cellular telephones (Grannell, 2013). If head-mounted displays are adopted for widespread use, then the differential effects of such systems on women and men could have consequences at the societal level.

The severity of motion sickness symptoms did not differ between women and men, in either experiment. Thus, in Experiment 2, while the incidence of motion sickness differed between the sexes the severity of symptoms did not. The same effect was reported by Koslucher et al. (2015). Taken together, these effects validate the conceptual distinction between motion sickness incidence and severity (e.g., Chen et al., 2012; Dong et al., 2011), and extend it to the domain of sex differences. In addition, the dissociation between the incidence of motion sickness and the severity of symptoms, both in general (e.g., Chen et al., Dong et al.) and in the context of sex differences (e.g., Koslucher et al.), may be an important area for future research. Such research could yield methodological benefits (e.g., it may be appropriate to use incidence as the primary criterion for motion sickness, rather than symptom severity), and it could yield more theoretically-oriented benefits (e.g., a better understanding of the type and severity of symptoms that lead a person to conclude, “I am motion sick”).

Postural precursors of motion sickness

Before participants used the Oculus Rift, I measured standing body sway during performance of simple visual tasks. In both experiments, patterns of sway during these pre-exposure tests differed between participants who later became motion sick and those who did not. There were no main effects of sickness groups on sway, unlike many previous studies (e.g., Koslucher et al., 2016; Stoffregen & Smart, 1998; Stoffregen et al., 2010). Rather, differences in sway between the Well and Sick groups were mediated by other factors, in statistically significant interactions.

In Experiment 1, the Visual Task × Sickness Groups interaction was significant, for the multifractality of postural sway (Figure 2). In Experiment 2, the Visual Task × Sickness Groups interaction was significant for the positional variability of the center of pressure, but was mediated by body axis in a 3-way interaction (Figure 4). These interactions may provide insight into the common anecdotal report that susceptibility to motion sickness can be influenced by variations in concurrent tasks, such as reading while riding in a car (Diels, 2014; Drummond, 2005).

We found effects in two qualitatively different measures, involving the spatial magnitude of sway, which I evaluated in terms of the positional variability of the center of pressure, and the temporal dynamics of sway, which I evaluated in terms of the width of the multifractal spectrum. Because the spatial magnitude and temporal dynamics of movement are orthogonal, these effects are independent.

Sex differences: Motion sickness and postural sway

In Experiment 2, patterns of postural sway that preceded motion sickness differed between women and men, as part of a 3-way interaction that included our variation in visual tasks (Figure 4). This result confirms that sex differences in the control of posture are precursors of sex differences in susceptibility to motion sickness (Koslucher, Haaland, & Stoffregen, 2016; Koslucher, Munafo, & Stoffregen, 2016), and extends the effect to contemporary head-mounted display systems. Of critical importance for theories of motion sickness etiology is the fact that sex-related differences in postural control exist before participants are exposed to any experimental motion, that is, before the onset of motion sickness. Differences in postural sway between participants who (later) become motion sick and those who do not have been found as much as 24 hours before participants were exposed to any experimental motion stimuli (Stoffregen et al., 2013, Experiment 3). Sex differences in postural sway are related to sexual dimorphism, that is, to physical differences in the bodies of men and women. Chiari et al. (2002) argued that most of the effects of sex on standing body sway can be traced to bio-mechanical properties, and not to "neural control."

Sex differences in motion sickness might be related to sex differences in cognitive function (e.g., Giammarco et al. 2015; Kimura 1997; Voyer et al. 1995). Our results, together with those of Koslucher et al. (2015), Koslucher, Haaland, and Stoffregen (2016) and Koslucher, Munafo, and Stoffregen (2016) support a qualitatively different hypothesis; that sex differences in susceptibility to motion sickness are related to sexual dimorphism and its consequences for the stability of movement.

The sensory conflict theory does not predict a sex difference in motion sickness; rather, adherents of the sensory conflict theory have offered explanations of the sex difference that are *ad hoc* (e.g., Golding, 2006). This absence of *a priori* prediction contrasts with the postural instability theory of motion sickness (Riccio & Stoffregen, 1991), as elaborated by Koslucher et al. (2015). In the postural instability theory, motion sickness follows instability in control of the body or its segments. Any factor that generates instability can, therefore, lead to motion sickness. The sexes differ in the kinematics of body sway, which leads to the prediction that sex differences in body sway should precede sex differences in motion sickness. The results of the current study are consistent with this prediction, and extend earlier research (Koslucher, Haaland, & Stoffregen, 2016; Koslucher, Munafo, & Stoffregen, 2016) to the domain of seated posture and head mounted displays.

Game adaptation versus technology adaptation

In general, motion sickness is associated with adaptation: One of the defining features of motion sickness is that the subjective symptoms fade with continued exposure to the nauseogenic stimulus. For this reason, in the present study I might suppose that the risk of motion sickness was related to prior video game experience. However, it is widely understood that adaptation occurs with respect to a particular stimulus. At sea, persons adapted to one sea state may again become sick when ship motion changes, such as during a storm (e.g., Stevens & Parsons, 2002). Similarly, adaptation to automobiles does not automatically confer immunity in aircraft, or on trains (e.g., Kennedy, Dunlap, & Fowlkes, 1990; Turner, 1999). NASA has spent many millions of dollars trying to develop better (i.e., more accurate) ground-based tests of susceptibility to sickness in orbit, with very little to show for it (e.g., Lackner & DiZio, 2006). These issues are of relevance in the present study because head-mounted displays differ qualitatively from other gaming platforms, such as console video games and handheld devices. In the present study, it is likely that some participants had extensive previous experience playing video games. However, none of our participants had any previous experience with head-mounted displays, and none of them had ever played the two games that were used in this study. For this reason, the idea that previous video game experience might have influenced motion sickness incidence in the present study would require the claim that adaptation to video games would transfer across technological platforms; specifically, from displays that were not head-mounted, and which did not update display content on the basis of participants' head movements to the novel technology of head-mounted displays in which visual content was updated in real time based on quantitative data about participants' head movements.

Head-mounted displays, such as the Oculus Rift, differ qualitatively from other gaming platforms, such as console video games and handheld devices. The qualitative difference is the fact that built-in sensors make it possible to use head movements as inputs to the game. This qualitative difference in design is universally acknowledged to be the central point and purpose of the technology. People use head-mounted displays because they are *different* from other gaming systems. Thus, taken together with general empirical findings on motion sickness adaptation, there is little reason to believe that adaptation to other types of gaming technologies would confer any benefit to participants in the present study.

Motion sickness in augmented reality technology

Recently there has been increased interest in augmented reality HMDs which display virtual content in the real world. A prolific number of AR devices are available on market (Software Testing Help, 2021), and these devices have gained traction as training tools in industry (Blanford, 2020). Unfortunately, motion sickness can be induced by visual content displayed by AR devices (Douglass et al., 2017).

The extent to which AR HMD devices are nausogenic is understudied. Hughes et al. (2020) found an AR application led to higher SSQ scores when used on an AR HMD device compared to a tablet device. Vovk et al., (2020) asked participants to complete medical tasks using an AR HMD device to display a video for instructions. They found participants experienced increased motion sickness symptoms, but determined that the effect was negligible. The nature of the training video was not described.

To my knowledge, no one has studied sex differences in motion sickness using an AR HMD device. Cheap AR devices are entering the market for retail use and training, but it's likely that sex effects in motion sickness susceptibility exist when using such devices. One caveat is that motion sickness susceptibility is contingent on the type of virtual content that's displayed (as demonstrated by differences in motion sickness incidence between experiment 1 and 2 in this dissertation). AR devices should be tested for sex differences in motion sickness using a similar methodology to experiment 1 and experiment 2 in this dissertation. That is, researchers should test sex differences in AR devices using linear motion patterns, and using virtual content that does not specify linear motion. The implications of such a study would help AR content creators make design choices in applications that do not discriminately increase motion sickness susceptibility in women (such as avoiding linear motion patterns), and reduce motion sickness incidence as a whole.

Design recommendations for mitigating VR HMD motion sickness

Riccio & Stoffregen's (1991) postural instability theory of motion sickness claims that motion sickness arises because of maladaptive strategies for controlling posture in a novel environment. Experiment 2 confirms Koslucher etl al.'s (2016) finding that sex differences in motion sickness susceptibility are related to control of posture prior to nausogenic exposure. This finding may be utilized by companies creating VR HMDs or VR content through two design strategies; 1) implemented an algorithm predicts an individual user's chance for motion sickness incidence and 2) implemented an algorithm that detects instability in head movement and then produces feedback to help a user restabilize their movement to prevent motion sickness.

The first design strategy of detecting instability that leads to motion sickness would build off Smart et al.'s (2002) use of a stepwise discriminant analysis to predict motion sickness incidence. Smart et al. used the positional variability, velocity, and range of head movements in all 3 axes to predict motion sickness incidence in 92% of their subjects. The head movement data Smart et al. used for their predictive analysis is collected by VR HMDs for free as part of the user experience.

To create a VR HMD system that detects motion sickness incidence a researcher would need to do two things. The researcher must implement an analysis of the user's head movement in the 3 axes. The collection of positional variability, velocity, and range are trivial to implement, and other nonlinear metrics could be coded for analysis as well. The researcher would then need a battery of postural data to compare the current user's data against. This battery of data would need to consist of users who do not become motion sick during VR experiences. The individual user's data would be compared against this reserve data set and a statistical likelihood for motion sickness incidence would be generated. The user's calculated likelihood for motion sickness could then be presented to a user who could decide whether to continue the experience. This strategy could also be used to help users decide if they should purchase a VR HMD. The challenge of implementing this design recommendation would be creating the battery of data for comparing a user's individual data against.

Building off the first strategy, a second design strategy from this dissertation would be to detect postural instability then present feedback that helps a user restabilize control of posture. To achieve this, an algorithm would need to be implemented into an HMD that detects postural instability using one or multiple metrics, which I would term *instability metrics*. Then, feedback would need to be presented to an individual to bring the instability metrics back into an acceptable range.

Let's take as an example an individual using a VR HMD to play a first person video game. The individual's head movements are detected in the video game and the visual display provides feedback about the virtual world from the point of view of the character. The user plays the game. Over the course of the session the VR HMD detects the user's head movements are consistently violating the acceptable range for instability metrics. The VR program then presents a green dot and a box in the user's visual feedback. The user is given instructions to move their head in such a way that the green dot is maintained inside of the box. The user follows these instructions, and maintains the dot inside the box. The user's instability metrics return to an acceptable range, and the user never becomes motion sick.

Conclusion

The postural instability theory of motion sickness (Riccio & Stoffregen, 1991) predicts that individual differences in the kinematics of postural activity will precede individual differences in susceptibility to motion sickness. In the present study, this prediction was confirmed in two experiments. Postural activity varies naturally as a function of many parameters of the body, including sex and, accordingly, the postural instability theory predicts that sex differences in postural activity will precede sex differences in motion sickness. In Experiment 2, I found evidence confirming this prediction in the context of a head-mounted virtual reality system.

Virtual reality technologies have been associated with motion sickness for more than 20 years (e.g., Stanney et al., 1998). Broadly, anecdotal reports of motion sickness among users of virtual reality systems have paralleled the evolution of these technologies: No one ever got sick playing *Pac-Man*, but today people can get queasy using a cell phone (Grannell, 2013). It is both ironic and frustrating that "better" technology has been associated with *more* motion sickness. The results of the present study are consistent with this trend. The incidence of motion sickness in our experiments (22%, in Experiment 1, and 56%, in Experiment 2) was remarkably high given that I limited exposure time to a maximum of 15 minutes.

It is widely accepted that women are at greater risk of motion sickness than men. This effect has been confirmed in vehicular travel, including seasickness (Lawther & Griffin, 1986, 1988), buses (Turner & Griffin, 1999), in the context of open-loop linear oscillation of the illuminated environment (Koslucher et al., 2015), and, in the present study, closed-loop motion of a virtual environment in a head-mounted display. In terms of sex differences in the incidence of motion sickness, head-mounted displays appear to be congruent with the general literature. I conclude that the Oculus Rift, as a technology, is sexist in its effects. To say that a technology is sexist in its effects does not implicate the intentions of its designers. The Oculus Rift is sexist in its effects because it has disparate impact on women and men (boyd, 2014). Documentation of these sexist effects, as in the present study, can motivate manufacturers to search for design changes that eliminate the discriminatory effects. Our results, together with those of Koslucher et al. (2015, Koslucher, Haaland, and Stoffregen (2016), and Koslucher, Munafo, and

Stoffregen (2016) suggest that solutions may be found by addressing aspects of design that influence users' ability to stabilize their own bodies.

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