International Journal of Human–Computer Interaction

ISSN: 1044-7318 (Print) 1532-7590 (Online) Journal homepage: https://www.tandfonline.com/loi/hihc20

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INTERNATIONAL JOURNAL OF HUMAN–COMPUTER INTERACTION
https://doi.org/10.1080/10447318.2020.1726108

Cybersickness in Virtual Reality Head-Mounted Displays: Examining the Influence of Sex Differences and Vehicle Control

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ABSTRACT

Motion sickness is more common among women than among men. In vehicles, motion sickness is more common among passengers than among drivers. We asked whether these two effects might interact. In a yoked-control design using a head-mounted display, one member of each pair drove a virtual automobile, while the other member watched a recording of the driver's performance. Overall reports of motion sickness were representative of previous research. We found no evidence that the incidence of motion sickness, or the severity of motion sickness symptoms differed between the sexes, or between drivers and passengers. However, among participants who discontinued early, the exposure time for female drivers was significantly less than for male drivers. The results confirm that motion sickness is a common effect of HMD use, and suggest that in virtual environments sex differences in motion sickness may vary with specific tasks.

1. Introduction

It is a commonplace observation that automobile passengers are more likely than drivers to experience motion sickness. This "driver-passenger" effect has been confirmed experimentally in physical vehicles (Rolnick & Lubow, 1991) and in virtual vehicles (Dong, Yoshida, & Stoffregen, 2011). In the present study, we focused on two aspects of the driver-passenger effect. First, we asked whether the driver-passenger effect would differ between men and women. Second, we asked whether the driver-passenger effect would occur in the context of head-mounted displays (HMDs). HMDs are remarkable technical achievements, and often give rise to compelling subjective experiences of realism, or *presence*. Unfortunately, these systems are associated with motion sickness, which is often referred to as cybersickness.

Cybersickness is a term commonly used to refer to the subset of motion sickness that occurs among users of virtual reality systems (McCauley & Sharkey, 1992). Regardless of the term used to refer to this phenomenon, there are widespread anecdotal reports in controlled research confirming the occurrence of motion sickness in HMDs (Draper, Viirre, Furness, & Gawron, 2001; Merhi, Faugloire, Flanagan, & Stoffregen, 2007; Munafo, Diedrick, & Stoffregen, 2017; Sharples, Cobb, Moody, & Wilson, 2008). Accordingly, HMDs seemed a good venue to investigate possible sex differences in the driver-passenger effect.

1.1. Sex differences

In most situations, women are more susceptible to motion sickness than men. Classic studies have documented this effect in seasickness and other types of vehicular travel (Golding, 2006; Lawther & Griffin, 1988; Turner & Griffin, 1999). Women also are more susceptible than men in the context of visually induced motion sickness (e.g., Koslucher, Haaland, Malsch, Webeler, & Stoffregen, 2015).

Sex differences in motion sickness may be especially problematic in HMDs. In two experiments, Munafo et al. (2017) examined motion sickness among users of a contemporary HMD system (the Oculus Rift DK-2). While playing a non-locomotor game (Experiment 1), in which rotational head movements were used to manipulate a game board, the difference in incidence between women and men was not significant. However, while playing a locomotor game (Experiment 2), in which the player used a handheld controller to walk freely within a virtual building, women (78%) were significantly more likely than men (33%) to state that they were motion sick. In the present study, we asked whether sex differences in visually induced motion sickness would extend to a virtual vehicle presented via an HMD.

1.2. Men and women, drivers and passengers

Rolnick and Lubow (1991) documented the driver-passenger effect in the context of inertial motion. They built a whole-body motion device that rotated around the vertical axis, carrying two participants. One participant controlled the rotation of the device, while the other did not. Participants in control of the device reported fewer symptoms of motion sickness than participants who were not in control. However, the experimental sample included only males. Several studies have examined the driver-passenger effect in the context of visually induced motion sickness, using virtual

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vehicles in video games. These studies have included women and men but have not analyzed the data for possible sex differences (e.g., Chang, Chen, Kung, & Stoffregen, 2017; Dong et al., 2011; Stoffregen, Chang, Chen, & Zeng, 2107; cf., Chen, Dong, Chen, & Stoffregen, 2012; Sharples et al., 2008; Stoffregen, Chen, & Koslucher, 2014). Accordingly, the existing literature provides no information about possible sex differences in the driver-passenger effect.

Given the generality of sex differences in motion sickness, it seems appropriate to ask whether differences between women and men may co-vary with the control of vehicles. Given the ubiquity of automobile travel, and the fact most adults have wide experience traveling as drivers and as passengers, it may seem remarkable that this question has not been addressed. Nevertheless, we are not aware of any studies, either observational or experimental, of possible sex differences in motion sickness relating to drivers and passengers of either physical or virtual vehicles. The present study was part of a larger project in which we also investigated the relationships between motion sickness and the kinematics of body sway: these data will be published separately.

2. Method

2.1. Participants

A total of 79 individuals participated (41 women and 38 men), in exchange for course credit. Participants ranged in age from 18 to 49 years (mean = 21.84 years, SD = 4.19 years), in height from 1.51 to 1.94 m (mean = 1.72 m, SD = 0.10 m), and in weight from 47.63 to 104.33 kg (mean = 71.58 kg, SD = 12.47 kg). The research protocol was approved in advance by the IRB of the University of Minnesota IRB (STUDY00001875).

2.2. Apparatus

We used the Oculus Rift CV1. The device comprised a lightweight (0.360 kg) headset that completely covered the field of view. The headset included separate displays for each eye, each with 1080 × 1020 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. Drivers controlled motion of the virtual automobile using a steering wheel and foot pedals (Thrustmaster Ferrari 458 Spider).

2.3. Procedure

Each participant gave informed consent and was informed they could discontinue at any time without penalty. Following the informed consent procedure, they 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), we 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. We asked whether participants currently played video games and, if so, how many hours per week. Information about participants' experience with video games is presented in Table 2. Information about participants' experience using HMDs is presented in Table 3.

Participants next removed their shoes and were measured for height and weight, after which they stood on the force plate for approximately 2 minutes. The portion of the study associated with the force plate will be published separately.

After the standing balance trials, participants sat on the stool and were shown how to adjust the Oculus Rift for comfort and visual clarity. Participants were shown the Oculus Home Screen and asked to adjust the HMD until the image was clear. Adjustments included repositioning the HMD, and changing the inter-pupillary distance. Once the participant confirmed the image was clear, the Experimenter explained the controls (for Drivers). Participants were reminded that they should discontinue immediately if they experienced any symptoms of motion sickness, however mild.

The participants played or watched game footage from a commercially available racing game, *Assetto Corsa*. Drivers drove a Ferrari 458 Italia on the Highlands Long Track. The course was 12 m wide, and 12 km in length. The overall shape of the course is shown in Figure 1. We chose the automatic transmission option. Drivers could shift into reverse (this was sometimes useful after crashes). We chose the drivers-eye view option. To increase realism, we selected the option to include one competing car on the course. The sound was played through desktop speakers.

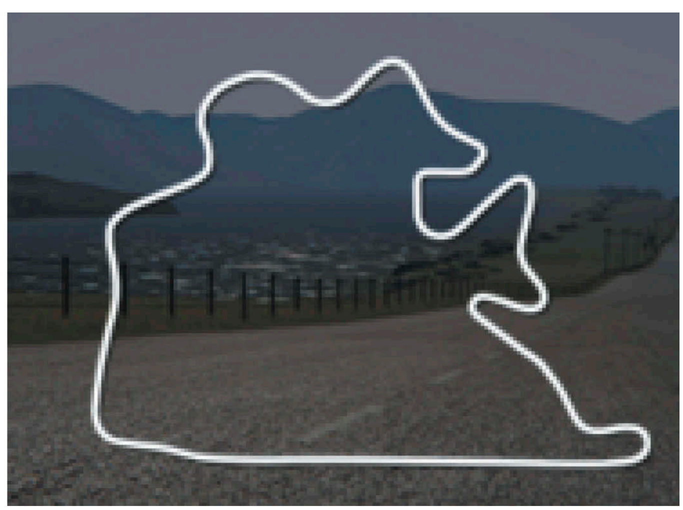

Figure 1. Overhead representation of the racetrack. The length of the simulated track was 12.19 km.

We used a between-participants, yoked control design with individual Passengers being yoked to individual Drivers. Each pair of participants was same-sex: men paired with men, and women with women. Separately for men and women, odd-numbered participants were assigned to the driver group, and even-numbered participants were assigned to the Passenger group. The recording from Participant 1 was viewed by Participant 2; the recording from Participant 3 was viewed by Participant 4, and so on. Participants were reminded to discontinue immediately if they experienced any symptoms of motion sickness, however mild. Participants played or viewed the game for up to 15 minutes. Participants in the Driver group were told that, during the first 3 min of play they could ask the experimenters for clarification with the driving controls, after which they were not given any additional assistance. Data on head and torso motion were collected continuously throughout the game session; these data will be reported elsewhere.

For Drivers who completed the 15 min session, their recorded performance was played for the corresponding Passenger until the Passenger completed the 15-min session or discontinued (whichever came first). If a Driver discontinued after at least 60 s, his or her recording was played to the corresponding Passenger. If that Passenger had not discontinued by the end of the (truncated) recording, the recording was restarted by the Experimenter, and replayed until 15 minutes were completed or until the passenger discontinued, whichever came first. Drivers who drove for less than 60 s before discontinuing were replaced, so that Passengers would view recorded driving sessions that were at least 60 s in duration.

After completing the 15-minute game exposure, or after discontinuation (whichever came first), participants completed SSQ-2, as well as the forced choice question asking them whether or not they were currently motion sick. If at SSQ-2, the participant stated they were not motion sick then they were given a printed copy of the SSQ (SSQ-3). Participants were instructed to complete this form if they began to feel motion sick at any time during the following 24 h or if they did not experience motion sickness, after 24 h. Previous research on motion sickness has shown that symptom onset may occur after the participant has left the lab (Stoffregen, 1985). Participants could return the SSQ-3 form either in person or by taking a picture of their completed form and emailing it to one of the Experimenters. If the participant did not return the SSQ-3, they were excluded from the study.

2.4. Data analysis

Following previous studies (e.g., Munafo et al., 2017; Stoffregen & Smart, 1998), participants were assigned to the Well and Sick groups based solely on their responses to the forced-choice, yes/no question, *Are you motion sick?*, at the time of SSQ-2 or SSQ-3. For the SSQ, we computed the Total Severity Score. Scores on the SSQ are not normally distributed and, for this reason, we analyzed SSQ data using nonparametric statistics, as recommended by Kennedy et al. (1993). The maximum possible Total Severity score on the SSQ was 235.62.

Repeated assessment of symptom severity could lead to inflated post-exposure severity ratings, as a function of demand character (Young, Adelstein, & Ellis, 2006; cf. Keshavarz & Hecht, 2011). However, there is no reason to expect that any effect of demand character would differ between the Well and Sick groups, given that group membership was determined solely on the basis of an independent assessment of motion sickness incidence.

For drivers, we evaluated game performance in terms of the number of laps completed, the mean driving speed (meters per second), and the mean number of crashes per lap. Laps completed and driving speed were provided by the game application. To identify crashes, experimenters reviewed recorded footage to determine the number of times the vehicle contacted the walls, or any other vehicle.

3. Results

3.1. Motion sickness incidence

The data are summarized in Table 1. The overall incidence of motion sickness was 43% (34/79). Of these, 33 stated they were motion sick at SSQ-2, and one at SSQ-3. Three participants in the Driver group discontinued after less than 60 s and therefore, as noted in the Method section, were replaced. This accounts for the fact that our dataset contains three more Drivers (41) than Passengers (38). For drivers, the incidence of motion sickness was 49% (20/41). For passengers, the incidence was 37% (14/38). These rates did not differ, $\chi^2 = 1.15$, $p > .05$. For women, the incidence of motion sickness was 44% (18/41). For men, the incidence was 42% (16/38). These rates did not differ, $\chi^2 = 0.26$, $p > .05$.

Table 1. Motion sickness incidence.

	Drivers		Passengers	
	Well	Sick	Well	Sick
Women	11	11	12	7
Men	10	9	12	7
	21	20	24	14

Table 2. Experience with interactive technologies, excluding head-mounted displays. Play games: do you currently play non-HMD video games? Age began: at what age did you begin to play non-HMD video games? Years playing: for how many years have you played non-HMD video games? Hours/week: how many hours per week do you play non-HMD video games?.

		Play games		Age began	Years playing	Hours/week
	n	Yes	No	Mean (SD)	Mean (SD)	Mean (SD)
Well	45	21	24	8.36 (3.33)	9.27 (5.79)	3.09 (5.92)
Sick	34	9	25	8.32 (3.52)	8.65 (6.15)	1.01 (2.10)

Table 3. Experience with head-mounted displays. Used an HMD: have you ever used a head-mounted displays? Own an HMD: do you own a head-mounted display system? Hours/week: how many hours per week do you currently play games using an HMD?.

		Used an HMD		Own an HMD		Hours/week
	n	Yes	No	Yes	No	Mean (SD)
Well	45	19	26	2	43	0.02 (0.15)
Sick	34	10	24	2	32	0.00 (0.01)

3.2. Symptom severity

First, we compared symptom severity scores between groups, with separate comparisons before and after game exposure. At pre-exposure (SSQ-1), scores did not differ between the men (mean = 8.76, SD = 13.62) and women (mean = 5.84, SD = 7.94), U = 725, p = .58, between the Well (mean = 6.15, SD = 9.34) and Sick (mean = 8.69, SD = 13.01) groups, U = 652, p = .24, or between Drivers (mean = 6.66, SD = 9.33) and Passengers (mean = 7.87, SD = 12.77), U = 738, p = .67. Following game play (SSQ-2, or SSQ-3), scores did not differ between the men (mean = 38.58, SD = 30.84) and women (mean = 40.41, SD = 33.26), U = 741.5, p = .71, or between Drivers (mean = 41.51, SD = 32.90) and Passengers (mean = 37.40, SD = 31.13), U = 726.5, p = .61. However, scores were higher for the Sick group (mean = 66.60, SD = 26.33) than for the Well group (mean = 19.22, SD = 17.22), U = 99, p < .001.

Next, within groups, we compared symptom severity scores before and after game exposure. Post-exposure SSQ scores were higher than pre-exposures scores for each within-group comparison. For females, pre-exposure mean = 5.84, SD = 7.93; post-exposure mean = 40.41, SD = 33.25, Z = 4.98, p < .001. For males, pre-exposure mean = 8.76, SD = 13.62; post-exposure mean = 38.58, SD = 30.84, Z = 4.74, p < .001. For Drivers, pre-exposure mean = 6.66, SD = 9.33; post-exposure mean = 41.51, SD = 32.90, Z = 4.85, p < .001. For Passengers, pre-exposure mean = 7.87, SD = 12.77; post-exposure mean = 37.4, SD = 31.13, Z = 4.88, p < .001. For Well, pre-exposure mean = 6.15, SD = 9.34; post-exposure mean = 19.12, SD = 17.22, Z = 4.03, p < .001. For Sick, pre-exposure mean = 8.69, SD = 13.01; post-exposure mean = 66.55, SD = 26.33, Z = 5.09, p < .001.

3.3. Discontinuation

Twenty-nine participants discontinued without completing the 15-minute game exposure. Each of these participants stated that they were motion sick and gave motion sickness as their reason for discontinuation. That is, each participant who discontinued without completing the 15-minute game exposure was assigned to the Sick group. Of the 29 participants who discontinued, 16 were women, and 13 were men, while 16 were Drivers, and 13 were Passengers. The overall mean time of discontinuation was 360 s (SD = 226.51). The Sex × Driving status interaction was significant, F(1, 25) = 4.71, p = .04, partial η^2 = 0.158 (Figure 2). The 95% confidence intervals revealed that, among Drivers, women (mean = 191.3 s, SD = 68.2 s; 95% CI = 50.9–331.8 s) discontinued earlier than men (mean = 457.7 s, SD = 77.3 s; 95% CI = 297.4–615.9 s). For Passengers, the difference between men and women was not significant.

3.4. Looping of footage

For drivers that discontinued before 15 minutes, their gameplay was replayed until 15 minutes was reached or until the

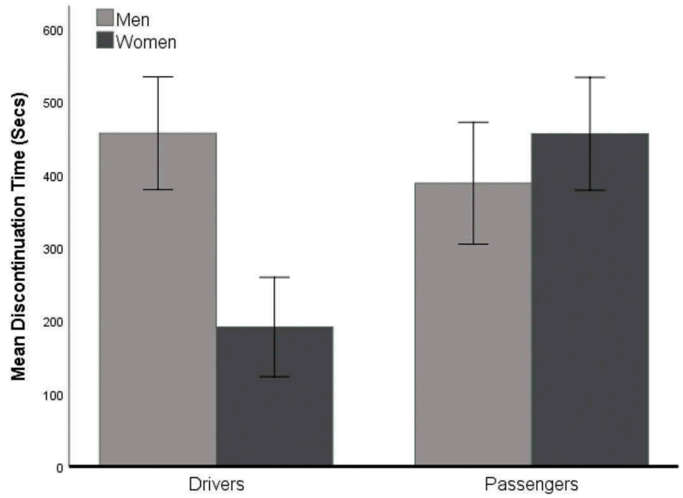

Figure 2. Mean time of discontinuation for the 29 participants who did not complete the 15-minute game exposure, illustrating the statistically significant Sex × Driving Status interaction. The error bars represent the standard error of the mean.

passenger discontinued; thus, some passengers were exposed to repetition of the driver's footage. To ensure this was not a confounding variable, we compared incidence among passengers that saw looped footage to those that did not. Among passengers who saw repeated footage, 36.4% stated they were sick, while among passengers who did not see repeated footage, 37.0% stated they were sick.

3.5. Game performance

For participants in the driver group, we evaluated game performance in terms of the number of laps completed, the mean number of crashes per lap, and mean driving speed. The number of laps completed differed between men (mean = 1.79, SD = 0.86) and women (mean = 1.14, SD = 0.94), U = 137, p = .045, and between the Well (mean = 2.10, SD = 0.44) and Sick (mean = 0.75, SD = 0.85) groups, U = 42.50, p < .001. The number of crashes per lap did not differ between men (mean = 14.08, SD = 8.70) and women (mean = 13.02, SD = 12.42), U = 173, p = .35, or between the Well (mean = 16.25, SD = 10.90) and Sick (mean = 10.64, SD = 10.03) groups, U = 137, p = .06.

The mean driving speed for laps completed was found to be normally distributed; thus, an independent-sample t-test was performed. A significant difference was found between women (mean = 32.74 m/s, SD = 4.34) and men (mean = 36.86 m/s, SD = 4.89), t(30) = 2.484, p = .019. The difference between the Well (mean = 35.49, SD = 4.84) and Sick (mean = 34.24, SD = 5.52) groups was not significant, t (30) = 0.66, p = .514.

4. Discussion

Participants were exposed to a driving video game presented via an HMD. The maximum exposure was 15 minutes. In a yoked-control design, half the participants controlled the virtual vehicle (Drivers), while half viewed drivers' recorded sessions (Passengers). Equal numbers of men and women were assigned to the driver and passenger groups. After game exposure, the incidence of motion sickness was 42%. The incidence of motion sickness did not differ between drivers and passengers, or between women and men. At post-exposure, the severity of motion sickness symptoms did not differ between women and men, or between drivers and passengers. Of the 34 participants in the Sick group, 29 discontinued game exposure without completing the 15-minute session. Of these 29, among Sick Passengers, the time of discontinuation did not differ between women and men. However, among Sick Drivers, women discontinued significantly earlier than men. We discuss these results in turn.

4.1. Motion sickness in head-mounted displays

The overall incidence of motion sickness was similar to other studies with video games (e.g., Stoffregen, Faugloire, Yoshida, Flanagan, & Merhi, 2008), virtual driving (Dong et al., 2011), and HMDs (Merhi et al., 2007; Munafo et al., 2017), as well as to virtual environments presented via video projection (Villard, Flanagan, Albanese, & Stoffregen, 2008). Symptom severity also was comparable to previous studies. We conclude that the nauseogenic properties of the driving game were representative of virtual environments, video games, and HMDs.

For participants in the Sick group, post-exposure ratings of symptom severity (SSQ scores) were greater than pre-exposure scores, as expected. However, we also found that post-exposure scores were greater than pre-exposure scores among participants in the Well group. This finding, which is common (e.g., Li et al., 2018; Munafo et al., 2017; Walter et al., 2019) underscores the logical distinction between the incidence of motion sickness (a yes/no dichotomy) and the severity of symptoms (a continuum). The distinction is important, also, because virtual reality systems, in general, and HMDs, in particular, are associated with an increase in certain symptoms, such as headache and eyestrain, among people who expressly deny being motion sick (e.g., Munafo et al., 2017; Stanney & Hash, 1998).

Among participants in the passenger group, exposure to repeated (looped) footage did not affect the likelihood of motion sickness.

4.2. The driver-passenger effect

We did not replicate the classic driver-passenger effect; that is, we found no evidence that passengers were more likely than drivers to report motion sickness. However, we did find that the overall incidence of motion sickness was representative of other studies of visually induced motion sickness. The representativeness of the overall sickness incidence and severity, coupled with the robustness of the driver-passenger effect in both physical (Rolnick & Lubow, 1991) and virtual driving (Dong et al., 2011) settings, lend credence to the idea that the present null result may constitute a novel effect. That is, it may be that the actual risk of motion sickness for drivers and passengers is equal in the context of HMDs. That being said, it always is difficult to interpret null effects, and future research is needed before such a conclusion could be reached.

It has been suggested that motion sickness in closed-loop virtual environments may be related to computational time lags between control inputs (e.g., head movements, in an HMD) and display outputs. However, controlled manipulations of time lag in experimental research have provided only mixed support for this hypothesis (e.g., Draper et al., 2001; Palmisano, Mursic, & Kim, 2017). Moreover, time lags in current iterations of HMD systems can be extremely short (Feng, Kim, Luu, & Palmisano, 2019). In the present study, time lag could have influenced motion sickness among drivers, but not among passengers. The fact that we found no differences in motion sickness incidence or severity between drivers and passengers provides no support for the hypothesis that time lag is an etiological factor for motion sickness in closed-loop VR systems.

It is widely argued that the subjective experience of self-motion (i.e., vection) may be causally related to visually induced motion sickness (e.g., Hettinger & Riccio, 1992). Kim, Chung, Nakamura, Palmisano, and Khuu (2015) examined vection among users of an HMD. They found that reported vection strength was greater when participants were passive viewers of virtual self-motion than when they actively controlled virtual self-motion. In the present study, we did not measure vection. However, if we assume that the effect reported by Kim et al., would have occurred, then vection should have been stronger among participants in our Passenger group than among participants in our Driver group. Our findings that the incidence and severity of motion sickness did not differ between these groups are not consistent with the hypothesis that vection is causally related to visually induced motion sickness.

4.3. Sex differences

We did not replicate the classic sex difference in motion sickness; that is, we found no evidence that women were more likely than men to become motion sick. Similarly, we found no evidence that women's symptom severity ratings were higher than men's symptom severity ratings. Munafo et al. (2017) studied motion sickness among HMD users. They found a sex difference in motion sickness incidence during an ambulation game (Experiment 2), but they found no sex difference when participants played a game that did not include locomotion (Experiment 1). It may be that, in the context of HMDs, sex differences in motion sickness incidence are related primarily to the control of ambulation. Clifton and Palmisano (2019) evaluated motion sickness among HMD users who controlled virtual ambulation, and also found no sex differences. It would be interesting, in future research with HMDs, directly to compare motion sickness among women and men in games featuring virtual ambulation and virtual driving.

In terms of motion sickness incidence and symptom severity, we found no evidence for the existence of sex differences in the driver-passenger effect. However, among those participants who discontinued early (all of whom stated they were motion sick), we found that the time of discontinuation (that is, the duration of exposure to the game) was influenced by a statistically significant interaction between sex and driver/passenger status (Figure 2). Among passengers, discontinuation time did not differ between the sexes, but among drivers, women discontinued earlier than men. This effect appears to be the first evidence that the driver-passenger effect can differ between the sexes. This effect, while modest, motivates future research. Perhaps the most obvious study motivated by the present results would be to evaluate possible sex differences in the driver-passenger effect in physical vehicles. This approach might be achieved using automobiles, or using laboratory whole-body motion devices, similar to Rolnick and Lubow (1991). Another approach might be to conduct a survey of a large sample of adults, specifically posing questions about experiences with "car sickness" as drivers, and as passengers, while requesting that respondents indicate their sex. Existing motion history questionnaires might be adapted to facilitate such a study (e.g., Golding, 2006).

4.4. Limitations

There are two principal limitations of this study. The first concern is the use of HMDs. It cannot be assumed that effects observed in the present study would generalize to other types of virtual environment systems, such as desktop displays, or projection displays. Future research is needed to address these issues. For example, the current study could be replicated using a console video game, rather than an HMD (cf., Dong et al., 2011).

It is equally important to acknowledge that while motion sickness is rare among drivers in physical driving, it is common among drivers in virtual driving, as occurs in driving video games (e.g., Chang et al., 2017; Dong et al., 2011; Nickkar, Jeihani, & Sahebi, 2019; Stoffregen et al., 2107), and in flight simulators (e.g., Stoffregen, Hettinger, Haas, Roe, & Smart, 2000). Motion sickness among drivers of virtual vehicles appears to be part of the larger problem of motion sickness associated with all forms of virtual locomotion (e.g., Chen et al., 2012; Munafo et al., 2017; Stoffregen et al., 2014).

5. Conclusion

In this present study, the influence of sex susceptibility and vehicle control on motion sickness was examined. In previous motion sickness research, it has been shown that women are more susceptible than men at becoming motion sick during VR exposure (Munafo et al., 2017). Additionally, prior research has shown that participants that are in control of either a physical (Rolnick & Lubow, 1991), or a virtual vehicle (Dong et al., 2011) are less likely to report motion sickness than those that are not in control. In terms of motion sickness incidence, we found no differences between males and females or between driving and passenger groups. Nevertheless, for drivers that discontinued early because of motion sickness, females had less VR exposure time than males. This difference between males and females suggests that sex differences in motion sickness may be dependent on the task being performed in the virtual environment. Future work is needed to better understand these specific tasks, thereby allowing mitigation approaches to be explored.

Acknowledgments

We thank Elisheva Savvateev, who assisted with data collection. Ms. Savvateev was supported by the University of Minnesota Undergraduate Research Opportunities Program.

Funding

Christopher Curry's participation was supported by the National Science Foundation [NRT-1734815]. Thomas A. Stoffregen's participation was supported by the National Science Foundation [CHS-1901423].

Disclosure of Potential conflict of interest

The authors declare that they have no financial interest in this work.

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