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Game Play in Virtual Reality Driving Simulation involving Head-Mounted Display and Comparison to Desktop Display

Shi Cao*, Krithika Nandakumar, Raiju Babu, and Benjamin Thompson

University of Waterloo, Canada

*Corresponding author

Address: Engineering 5, 6th Floor, 200 University Avenue West, Waterloo, Ontario, Canada N2L 3G1

Phone: 519-888-4567 ext. 36377

Email: shi.cao@uwaterloo.ca

ORCID: 0000-0002-6448-6674

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Abstract

Previous studies have reported the effect of driving simulator games on simulator sickness and eye symptoms experienced by users; however, empirical results regarding the game experience using commercial virtual reality head-mounted displays (VR-HMDs) are lacking. We conducted an experiment where participants played a driving simulator game (Live for Speed) displayed through an Oculus Rift DK2 for up to 120 minutes. Game play duration was recorded. Game experience was surveyed using questionnaires about simulator sickness, eye symptoms, and game engagement. The results showed that the average game play duration for this specific driving simulation game was approximately 50 minutes. Simulator sickness was negatively correlated with affordable play duration using the VR-HMD. We also found that age was negatively correlated with game play duration. There were no differences between those who did and did not wear frame glasses. In addition, we compared the VR-HMD game play and traditional desktop LCD game play, in terms of simulator sickness, subjective eye symptoms, game engagement, and game performance. The results showed that VR-HMD game play in the driving simulation game was similar to the experience using the desktop LCD display, except for a moderately increased level of simulator sickness. These findings provide new data about VR-HMD's impact on game play and will inform game designers, players, and researchers for their choices and decisions on proper game duration and the type of devices.

Keywords: virtual reality; driving simulation games; user experience; HMD; simulator sickness; eye symptoms.

1. Introduction

Virtual reality (VR) is being increasingly used in sport and game industries (Badcoe 2000; Neumann et al. 2017). For example, VR has been widely used in first-person driving simulation games. The immersive experience is brought to a new level by head-mounted displays (HMDs). Because of the rapid development of virtual reality HMDs, commercial models for gaming purposes are becoming widely available at an affordable price. For example, the prices of Oculus Rift and HTC Vive are around US$800. However, there are concerns regarding factors that may limit the adoption of VR-HMDs such as simulator sickness and eye fatigue (Patterson et al. 2006). In the research literature, there is a lack of empirical results regarding these factors that can be used to inform VR-HMD game designers and players. It is important that human factors must be carefully considered in the development of VR (Chen et al. 1998). In the current study, we conducted an experiment, in which participants played a driving simulator game using a commercial HMD. The goal was to measure the amount of time for which participants could comfortably play the VR-HMD driving simulation game, as well as to examine individual difference in the game experience. The Oculus Rift DK2 HMD was used in this experiment.

Playing simulation and virtual environment games can induce motion sickness (Stanney et al. 1999). Sensory conflict theory states that motion sickness is caused by a disagreement or mismatch between different sensory systems regarding the perceived movement (Treisman 1977). Simulator sickness refers to motion sickness experienced in simulated virtual environments (Rebenitsch and Owen 2016). In this case, the motion is usually seen by the visual system but not felt by the vestibular system, which causes a perceptual conflict (Bles et al. 1998). In addition to the sensory conflict theory, postural instability and insufficient vestibular-ocular correction have also been used to explain how simulator sickness occurs. Postural instability theory (Riccio and Stoffregen 1991) states that motion sickness occurs when people are presented with an environment where they do not have effective strategies to maintain a stable posture. Regarding vestibular-ocular factors, Ebenholtz (1992) hypothesized that motion sickness occurs when the vestibular-ocular system cannot sufficiently adjust ocular convergence, accommodation, and fusion to compensate for motion within a virtual environment. This theory has received support from behavioral and brain imaging results (Guo 2014; Miyazaki et al. 2015). Therefore, stronger visually induced motion sickness may be associated with increased eye symptoms due to increased or unusual load on the vestibular-ocular, convergence and accommodation systems. Gamers experiencing simulator sickness usually experience dizziness and nausea, and may even vomit in severe cases. Simulator sickness has a negative impact on game enjoyment (Lin et al. 2002).

A considerable number of studies have examined simulator sickness in virtual environments presented using traditional displays (not HMDs). In a report of flight simulator results from over 700 pilots, about 45% of participants reported some level of simulator sickness (Kolasinski 1995). Most of them reported that the symptoms would disappear within one hour. In a review of 10 driving simulator studies, Classen, Bewernitz, and Shechtman (2011) concluded that age, gender, and field of view all affect simulator sickness. In general, older participants (around 50 to 70 years old) experienced more symptoms than younger participants (around 20 to 40 years old) (Keshavarz et al. 2017). Women in general experienced more symptoms than men (Koslucher et al. 2016).

It is still unclear what causes the age and gender differences. Some researchers suggested that the age difference may be related to changes in the central nervous system, and the gender difference may be a result of evolution (McCaffrey and Graham 1980; Golding 2006). In general, a larger field of view contributed to a higher level of presence, stronger feeling of self-motion, and also higher simulator sickness scores (Classen et al. 2011; Palmisano et al. 2017).

A number of additional factors that affect the level of simulator sickness experienced by subjects in virtual environments have been identified. For example, faster object motion within a virtual environment results in stronger sensations of motion sickness (Hu et al. 1989). While VR technology aims to increase the level of detail, presence, and visual fidelity, it is suggested that these factors might also increase visually induced motion sickness as a side-effect (Hettinger and Riccio 1992). In addition, previous studies (Kennedy et al. 2000; Domeyer et al. 2013) using traditional displays have found that the level of simulator sickness increased with exposure duration (i.e., continuous play with no break) and that simulator sickness decreased with repeated exposure (i.e., playing the same simulator multiple times). Results from a recent study (Helland et al. 2016) also showed that higher blood alcohol concentration was associated with lower subjective simulator sickness scores, suggesting that alcohol may reduce perceived simulator sickness. Regarding interventions to mitigate simulator sickness in driving simulators, one study showed that galvanic cutaneous stimulation reduced subjects' simulator sickness scores (Gálvez-García et al. 2015), and another study showed that transdermal scopolamine reduced susceptibility to simulator sickness especially for female participants (Chaumillon et al. 2017).

Only a limited number of studies have examined game experience and simulator sickness with VR-HMD. Since VR-HMD is expected to increase presence and immersion, it might also increase simulator sickness. Indeed, existing studies have reported that simulator sickness resulting from using VR-HMD was stronger than using ordinary displays (Howarth and Costello 1997; Häkkinen et al. 2006). It was also found that playing VR-HMD games while standing induced a higher level of simulator sickness than playing the same game while seated (Merhi et al. 2007).

Regarding the duration of play, existing studies usually asked participants to play for no more than an hour. In one study using a VR chess game (up to 60 minutes), 4 of the 20 subjects (20%) stopped playing early due to headache and nausea with an average play time around 40 minutes (Howarth and Costello 1997). In another study using a VR action game (Whacked on XBox, up to 50 minutes), 10 of the 17 subjects (59%) discontinued play due to simulator sickness with an average play time of around 14 minutes (Merhi et al. 2007). In a recent study using VR roller coaster games (Parrot Coaster and Helix Coaster, maximum play time of 14 minutes), 10 of the 24 subjects (42%) dropped out early due to nausea with an average play time of approximately 5 minutes (Davis et al. 2015).

In previous studies examining driving simulators and simulator sickness, most of the simulators were for driving research purposes rather than gaming, and most of the displays were LCD or projectors rather than HMD (Brooks et al. 2010; Hamel et al. 2013; Bridgeman et al. 2014; Jäger et al. 2014). In a study using a vehicle in the loop simulator with an HMD (Karl et al. 2013), participants completed two daily driving scenarios for about 30 minutes each with breaks in between. Two of the 44 subjects could not finish due to simulator sickness, and approximately 11% of the remaining subjects reported severe simulator sickness symptoms. Since most driving games are racing games that involve faster driving speed and more aggressive maneuvering than daily driving, the amount of virtual motion in VR driving games might be greater than that usually presented in driving simulators for driving safety research.

It is not surprising that the type of VR games affects how long people can comfortably play the game. The more virtual motion presented in a game, the shorter the play duration becomes. In the current study, we focused on a driving simulator game (Live for Speed), which was expected to involve a moderate level of virtual motion, more than a chess game but less than a roller coaster game. We also intended to test longer VR-HMD game play time. It is generally believed that most people can play non-HMD games and watch non-HMD movies continuously for 90 minutes without any discomfort (Rau et al. 2006). Therefore, it is meaningful to test whether people can play VR-HMD driving simulator games for the same duration. As a result, we extended the maximum play time to 120 minutes in the current study.

Simulator sickness is often measured using subjective evaluation methods that ask participants to rate the severity of symptoms after experiencing the simulator. Two frequently used measures are the Motion Sickness Assessment Questionnaire (MSAQ) and the Simulator Sickness Questionnaire (SSQ). The MSAQ (Gianaros et al. 2001) asks 16 questions about symptoms in four dimensions: gastrointestinal (stomach sick, queasy, nauseated, vomit), central (faint-like, lightheaded, dizzy, spinning, disoriented), peripheral (sweaty, clammy, hot/warm), and sopite-related (annoyed, drowsy, tired, uneasy). The most recent version of the MSAQ (Davis et al. 2008; Brooks et al. 2010)

(Brooks et al. 2010)requires participants to rate each symptom on a scale from 0 (not at all) to 10 (severely). The overall score is the average from all the questions linearly transformed onto a range from 0 to 100. The SSQ (Kennedy et al. 1993) asks 16 questions about symptoms in three dimensions: nausea, oculomotor disturbances, and disorientation. Each question is rated on a scale of 0 (none), 1 (slight), 2 (moderate), and 3 (severe). The overall score is a weighted average from all the questions following a specific weighting scheme (Kennedy et al. 1993).

Eye symptoms are also related to video game play, in a way similar to viewing computer displays for prolonged period of time. The combined eye and vision problems are referred to as computer vision syndrome (CVS), for example, eyestrain, ocular discomfort, eye dryness, double vision, and blurred vision (Rosenfield 2011). A frequently used measure of eye sensation is the Current Symptoms Questionnaire (CSQ). It asks 10 questions relating to eye discomfort, dryness, blur, soreness and irritation, grittiness and scratchiness, something in eye, burning and stinging, sensitive to light, itching, and overall symptoms. Each question is rated on a scale from 0 (do not have this feeling) to 5 (very intense). The total score (ranging from 0 to 50) is the sum from all the questions. The CSQ is effective in classifying subjects with and without a prior diagnosis of dry eye, and the CSQ is a valid measure for the assessment of eye dryness and discomfort (Situ et al. 2013). In the current study, we used CSQ to measure eye symptoms related to playing the VR-HMD game.

Regarding game engagement, a frequently used measure is the Game Engagement Questionnaire (GEQ). The GEQ (Brockmyer et al. 2009) asks 19 questions about four aspects of game engagement, including psychological absorption, flow, presence, and immersion. Each question is rated on a scale from 0 to 4, and the overall average score is also on a scale from 0 to 4. The GEQ has shown good reliability and validity. It is regarded as a psychometrically strong measure of levels of engagement elicited while playing video games (Brockmyer et al. 2009). GEQ has been used in previous studies to measure game engagement, for example, in first-person shooter and driving simulator games (McMahan et al. 2012; Darty et al. 2014). We used the GEQ to measure game engagement in the current study.

In addition to the duration of play in VR-HMD, another interesting research question is whether there is any significant difference between VR-HMD and desktop LCD. After the completion of Study 1 that focused on game play duration in VR-HMD, we conducted Study 2 in order to further compare the VR-HMD game play with traditional desktop LCD game play, in terms of measures including simulator sickness, subjective eye symptoms, game engagement, and game performance.

Study 1: Game Play Duration in VR-HMD

2. Method of Study 1

2.1. Participants. Forty-seven adults (35 males and 12 females, mean age 25 ± 5 years, range 18-38 years) were recruited around the campus of University of Waterloo. All participants self-reported normal or corrected-to-normal vision. They had played video games for 13 ± 7 years and usually played for 7 ± 9 hours per week. Nine participants reported previous experience with VR-HMDs, but their experience was very limited at only 5 ± 7 hours. Twenty-two participants wore frame glasses, 10 participants wore contact lenses, and the remaining 15 participants wore no glasses. Participants with frame glasses were able to wear their glasses inside the HMD unit.

2.2. Apparatus. The driving simulator game was Live for Speed (S2 0.6G version, as shown in Figure 1). It is a serious racing simulator with realistic physics and vehicle dynamics simulation. The driving scene used for the experiment was a racing track (3.3 km circuit). The simulated vehicle was a model called XF GTI in the game (engine power 86 kW, torque 130 Nm, total mass 942 kg). Typical driving speed in the game ranged around 90 to 180 km/h. The VR-HMD used was Oculus Rift DK2, which has a resolution of 960×1080 pixels per eye, a refresh rate at 75 Hz, and 100° field of view supporting 3D vision (binocular disparity). The desktop PC used to run the game was an Acer Predator G3 model with i7-4790 CPU (3.60GHz), 12GB RAM, GeForce GTX 760 GPU, and Windows 8.1 OS. Audio was played via Bose Companion 2 Series III speakers. The steering wheel and pedal set was Logitech G27. Figure 2 shows a user playing the game wearing the VR-HMD. The average frames per second (fps) was 90.

Figure 1. A scene from the driving simulation game (Live for Speed) used in the current study.

Figure 2. A user playing the game wearing the VR-HMD.

2.3. Measures. Game play duration: participants were instructed to play for as long as they felt comfortable up to a maximum of 120 minutes. They were told that they should stop playing at any time if they felt necessary. The experimenter recorded the play time with a stopwatch. Every 15 minutes, the experimenter asked participants whether they preferred to stop playing or keep playing. The final total duration of play was recorded as game play duration. If a participant reached the 120-minute limit, the experimenter would stop the experiment as this was the maximum time permitted. Simulator sickness was measured using the most recent version of MSAQ (0-100 range). Eye symptoms were measured by CSQ (0 to 50 range). Game engagement was measured by GEQ (0 to 4 range). In addition, ocular measures including visual acuity, tear break-up time, tear meniscus height, ocular redness, and corneal staining were also recorded, which will be reported elsewhere.

2.4. Procedure. The experiment was approved by an ethics review committee at the University of Waterloo. Upon arrival, participants first read the information letter and signed the consent form. They completed a background survey questionnaire with their demographic information and previous game experience. Then the experimenter introduced the HMD unit and helped the participants wear it properly. Participants played the game while seated. Before the formal experiment, they practiced for 5 minutes. The practice session also gave the opportunity for participants to quit the study if they did not feel comfortable and could not use the VR-HMD at all. A pre-game CSQ was completed to measure the baseline level of eye symptoms, and then participants started the formal play for up to 120 minutes. Every 15 minutes, the experimenter asked participants whether they preferred to stop playing or keep playing. At the end of the play period, participants completed a post-game CSQ (same as the pre-game version), MSAQ, and the GEQ. Then they were debriefed, paid (Can$20), and thanked for their participation.

3. Results of Study 1

Statistical analyses were conducted using SPSS. Questionnaire scores were available from 42 participants who completed the formal driving session.

3.1. Play duration. One participant's play duration value was missing due to a clerical error. Valid play duration datasets were collected from 46 participants. Among them, 5 participants discontinued after the practice session due to strong discomfort and simulator sickness, so their play duration values were recorded as 0 minutes. Overall the mean play duration was 51 ± 33 minutes (Figure). Four major groups of play duration were identified, including cannot play at all (less than 1 minute; 5 persons, 11%), short duration (1 to 44 minutes; 10 persons, 22%), medium duration (45 to 89 minutes; 24 persons, 52%), and long duration (over 90 minutes; 7 persons, 15%).

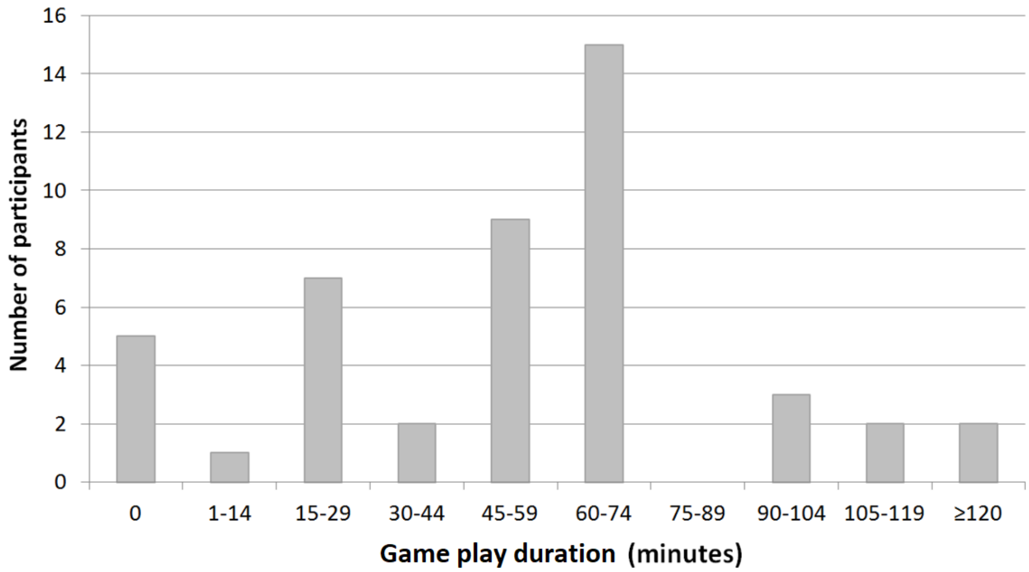

Figure 3. Distribution of game play duration for playing a driving simulator game using a VR-HMD. The maximum play time allowed in this study was 120 minutes.

3.2. Simulator sickness. The average MSAQ score was 30 ± 24. Note that the possible range of the MSAQ is 0 to 100. The Pearson correlation between MSAQ and game play duration was significant (r = -0.56, p < 0.001). The scatterplot is shown in Figure 4. The negative correlation coefficient indicated that people who experienced stronger simulator sickness played the game for less time. Further analysis divided the data set into two halves at the median MSAQ value of 29, which resulted in two groups, low MSAQ (N = 21, *Mean* = 10, *SD* = 8) and high MSAQ (N = 20, *Mean* = 50, *SD* = 18). An independent-samples T test showed that play duration for the high MSAQ group (*Mean play duration* = 39 min, *SD* = 21 min) was significantly shorter than play duration for the low MSAQ group (*Mean play duration* = 75 min, *SD* = 24 min), $t(39)$ = 5.111, p < 0.001, d = 1.6. This result was in accordance with the correlation analysis finding.

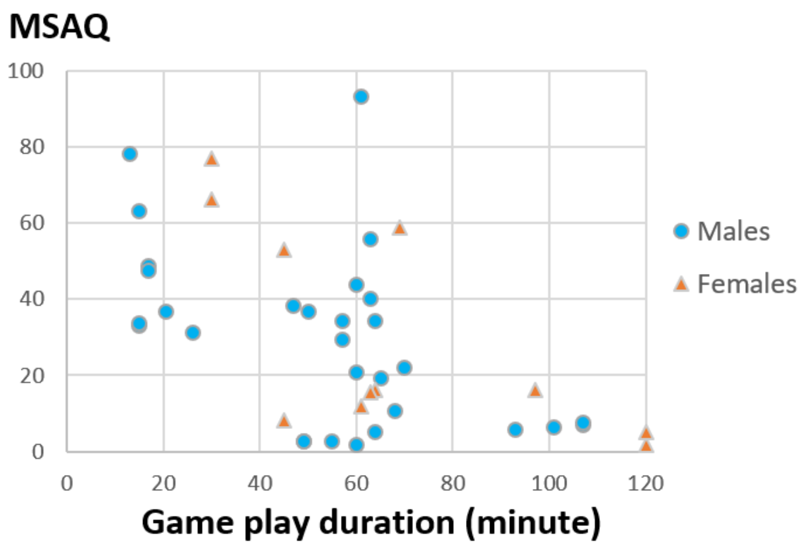

Figure 4. Scatterplot of participants' MSAQ score vs game play duration.

3.3. Eye symptoms. The CSQ was measured before and after the formal driving session. A CSQ-difference score was computed as post-game CSQ minus pre-game CSQ. The difference has a possible range from -50 to 50. Overall, pre-game CSQ had an average value of 4.1 ± 4.5, and the post-game CSQ average was 7.4 ± 5.6. A paired sample T test showed that CSQ significantly increased after playing the game, $t(41) = -4.75$, $p < 0.001$ (two-tailed), $d = 0.65$. The average CSQ-difference was 3.3 ± 4.5. The correlation between CSQ-difference and play duration was not significant ($r = -0.14$, $p = 0.38$); the correlation between CSQ-difference and MSAQ was significant ($r = 0.35$, $p = 0.02$), meaning that participants who reported more eye symptoms also reported stronger simulator sickness. Further analysis divided the data set into two halves at the median CSQ-difference value of 2.0, which resulted in two groups, low CSQ-difference ($N = 19$, *Mean* = -0.2, $SD = 1.2$) and high CSQ-difference ($N = 22$, *Mean* = 6.5, $SD = 4.0$). An independent-samples T test showed no significant difference in play duration between the two groups, $t(39) = 1.853$, $p = 0.07$, $d = 0.9$. This result was in accordance with the correlation analysis finding.

3.4. Game engagement. The average GEQ score was 1.2 ± 0.4. There were no significant correlations between GEQ and play duration ($r = -0.02$, $p = 0.91$), MSAQ ($r = 0.08$, $p = 0.63$), or CSQ-difference ($r = -0.01$, $p = 0.97$).

3.5. Age and gender. Analysis of covariance (ANCOVA) was conducted to examine the effects of age and gender on play duration. The results showed a significant effect of age on game play duration, $F(1, 43) = 13.76$, $p = 0.001$, $\eta^2 = 0.07$. Figure 5 shows a scatterplot of age vs game play duration. The effect of gender on play duration was not significant, $F(1, 43) = 0.03$, $p = 0.86$, $\eta^2 < 0.001$. Table 1 shows play duration values and 95% confidence intervals for both the male and the female groups. Overall, there was a significant inverse correlation between age and play duration ($r = -0.52$, $p < 0.001$), indicating that younger participants played the game for longer.

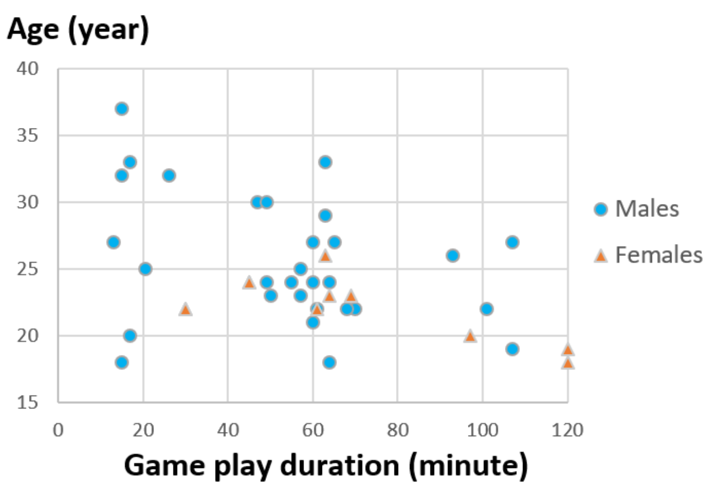

Figure 5. Scatterplot of participants' age vs game play duration.

Table 1. Game play duration by gender.

Gender	N	Play duration mean ± SD (minute)	95% confidence interval
Male	34	47.3 ± 30.9	36.9 to 57.7
Female	12	62.0 ± 36.3	41.5 to 82.5

3.6. Playing the game with frame glasses. A T test (two-tailed) was conducted to compare play duration between participants who wore frame glasses and participants who did not wear frame glasses (contact lenses or no correction). Table 2 shows play duration values and 95% confidence intervals for participants with and without frame glasses, which showed no significant differences ($t(44) = 0.29$, $p = 0.77$, $d = 0.09$). Since age showed a significant effect on play duration, we also conducted an additional ANCOVA with variable of glasses condition and age in the model. The effect of glasses condition remained non-significant, $F(1, 43) = 0.002$, $p = 0.97$, $\eta^2 < 0.001$, whereas the effect of age was significant, $F(1, 43) = 15.96$, $p < 0.001$, $\eta^2 = 0.08$. An ANOVA with a factor of Group (i.e., people with frame glasses, contact lenses, and no correction) and a covariate of Age showed the same results; there was no significant difference between the three groups, $F(2, 42) = 0.081$, $p = 0.92$, $\eta^2 < 0.001$, whereas the effect of age was significant, $F(1, 42) = 15.78$, $p < 0.001$, $\eta^2 = 0.08$.

Table 2. Game play duration by wearing frame glasses or not.

	N	Play duration mean ± SD (minute)	95% confidence interval
With frame glasses	22	52.6 ± 32.3	39.1 to 66.1
Without frame glasses	24	49.8 ± 33.6	36.3 to 63.2

Study 2: Comparison between VR-HMD and desktop LCD

After the completion of Study 1, we conducted another study in order to further compare the VR-HMD game play with traditional desktop LCD game play. The research question focused on whether there would be any significant difference on simulator sickness, subjective eye symptoms, game engagement, and game performance.

4. Method of Study 2

4.1. Participants and apparatus. A subset of participants from Study 1 continued to participant in Study 2, including 28 adults (20 males and 8 females, mean age 24 ± 3 years, range 19-33 years). All participants self-reported normal or corrected-to-normal vision. They had played video games for 13 ± 5 years and usually played for 7 ± 9 hours per week. The apparatus was the same as in Study 1, with an additional desktop LCD display (27 inch).

4.2. Measures and procedure. The procedure was generally the same as the procedure of Study 1, with the additional of the desktop LCD condition. The measures included simulator sickness (MSAQ), subjective eye symptom report (CSQ), game engagement (GEQ), and game performance (best lap time, in seconds, recorded in the driving simulation game). In order to allow a fair comparison, the game play duration was set to be the same for both conditions of VR-HMD and desktop LCD. It was set at 45 minutes, which was at the lower end of medium duration identified in Study 1. A within-subject design was used, with the order of experiencing the two displays balanced across subjects. The experiment was completed in two sessions with a few days apart.

5. Results of Study 2

5.1. Simulator sickness. Paired sample T test of MSAQ scores showed that the VR-HMD condition (15.2) resulted in significantly higher level of simulator sickness than the desktop LCD condition (5.0), $t(27) = 2.875$, $p = 0.008$, $d = 0.543$.

5.2. Eye symptoms. Repeated measures ANOVA was used to analyze the CSQ data with two within-subject factors, pre-post (before or after game play) and device (VR-HMD or desktop LCD). The effect of pre-post was significant; post-game CSQ (6.8) significantly increased in comparison to pre-game CSQ (4.4), $F(1, 25) = 6.255$, $p = 0.019$, $\eta^2 = 0.12$. The effect of device was not significant, $F(1, 25) = 1.120$, $p = 0.300$, $\eta^2 = 0.01$. The interaction effect was not significant, $F(1, 25) = 1.571$, $p = 0.222$, $\eta^2 = 0.01$.

5.3. Game engagement. Paired sample T test of GEQ scores showed no significant difference between the VR-HMD condition (1.1) and the desktop LCD condition (0.9), $t(25) = 1.522$, $p = 0.140$, $d = 0.299$.

5.4. Game performance. Paired sample T test of best lap time (in seconds) in the driving simulation game showed no significant difference between the VR-HMD condition (109 s) and the desktop LCD condition (109 s), $t(26) = 0.011$, $p = 0.991$, $d = 0.002$.

6. Discussion

How long can people play the VR-HMD driving simulation game? When interpreting the results from the current study, it is important to remember that the type of game will certainly affect comfortable play duration, and the current study focused on a specific driving simulation game. The results suggested that large individual differences exist regarding play duration for playing the VR-HMD driving simulator game. Four major groups of play duration were identified, including cannot play at all (less than 1 minutes; 11%), short duration (1 to 44 minutes; 22%), medium duration (45 to 89 minutes; 52%), and long duration (over 90 minutes; 15%). Overall, the average play duration was 51 minutes. About half of the participants could not play continuously for an hour. In contrast, most people can play non-HMD games and watch non-HMD movies for 90 minutes. To measure play duration in a relatively natural condition, we simply asked participants to play for as long as they felt comfortable up to a maximum of 120 minutes. Although the observer effect may occur, which means that participants may choose to play longer because they know they are being observed, we did not intend to push participants to the limit of discomfort and therefore told them that they should stop playing at any time if they felt necessary. Participants were aware that they were paid the same amount regardless of their actual game play duration. As a result, we expect that the measured play duration could reflect natural game play behavior of the participants.

Regarding the causes of motion sickness in VR games, a major factor is the amount of virtual motion presented in the game. Different types of games involve different levels of virtual motion. People tend to reply on horizontal and vertical lines in the view to establish the perception of orientation and balance in the virtual world (Andre et al. 1996). When these visual references are moving or when no such references are presented, players may suffer from more motion sickness and therefore can only afford shorter play duration (Shafer et al. 2018). In this regard, roller coaster games are expected to induce stronger motion sickness than driving games. In addition, faster head movement in VR games is associated with stronger motion sickness (Moss and Muth 2011). To provide a comparison of game play duration across different types of games, as shown in Table 3, we compared the game play duration from the current study and the values reported or estimated from other studies in the literature. Although different studies may have different maximum duration of play allowed in the experiment, the comparison is still meaningful because a significant number of participants stopped playing due to motion sickness and discomfort before the maximum duration. While people are expected to play a chess game for longer duration than a racing game, the opposite results shown in Table 3 may be explained by the fact that the chess game was played using an earlier model of VR-HMD device. The poorer display quality (lower resolution) of the old VR device might be a factor leading to shorter play duration.

Table 3. Comparison of VR-HMD game play duration across different types of games.

Study	**Type of game**	**VR-HMD device**	**Average play duration (minutes)**
(Davis et al. 2015)	Roller coaster riding	Oculus Rift	10
(Merhi et al. 2007)	Third-person 3D action	Visette Pro	27
This study	Car racing	Oculus Rift	51
(Howarth and Costello 1997)	Chess	Virtual i-glasses	42
(Kosunen et al. 2016)	Meditation in a park	Oculus Rift	≥60

The duration of play is an important factor in game design (Schell 2014). Too short a time may prevent players from enjoying the game and developing meaningful strategies, whereas too long a time may lead to boredom and tiredness. In VR-HMD game design, the potential of simulator sickness represents a new factor to consider when designing the duration of play. The results from the current study may help game designers determine the proper duration of each game scenario, providing sufficient break time and reminders for gamers to take a rest between game sessions in order to minimize discomfort. Because VR-HMD games are relatively new, it is not clear how much this issue is considered by game designers in the industry right now, and we could not find any related reports in the literature. In future studies, interviews with VR-HMD game designers should be conducted to further explore this issue and better understand the trade-off between longer and shorter game play duration.

Based on our results, we recommend that gamers who are interested in purchasing VR-HMD systems try them first before making the purchase. The current results from a game with a moderate level of virtual motion seem to show that the group of people who will experience the strongest level of motion sickness can feel it in a short duration of play around 15 minutes. If they can do that, usually they could play for much longer time such as over 45 minutes. This grouping effect of individual difference is also shown in previous studies (Merhi et al. 2007). It suggests that a quick play is a good way to screen out people who may suffer from strong motion sickness playing VR-HMD games. While it is important to find each individual's play duration, most participants (85%) in the current study had a play duration that was shorter than 75 minutes. This result could help determine a recommendation for VR-HMD driving simulation play time in the future.

Future studies are needed to examine the effects of other factors on game play duration; for example, VR game settings such as resolution and refresh rate may affect game play duration. It will also be necessary to study other types of games to assess the extent to which game play duration varies across game genres.

The results from the current study suggest that simulator sickness is a factor limiting game play duration. A significant negative correlation coefficient (r = -0.56) was found between MSAQ and play duration. Participants who experienced stronger simulator sickness tended to stop playing earlier. Previous studies (Kennedy et al. 2000) found that simulator sickness increased as the same individuals were continuously exposed to the virtual environment for longer durations. In those experiments, simulator sickness was measured multiple times for the same individuals as play time increased. Building on this earlier work, we found that participants with longer play duration reported less simulator sickness than participants with shorter play duration. Together, these results suggest that individual differences have a larger impact than exposure duration on simulator sickness.

The current results suggest that playing the VR-HMD game modestly increases eye symptoms. The average CSQ score was significantly increased from 4.1 to 7.4 with a mean increment of 80% relative to baseline. Note that the CSQ score range is from 0 to 50, so the level of symptoms was mild. There was a significant correlation between reported eye symptoms and reported simulator sickness. Although the two questionnaires have no direct overlap in terms of questions, both sets of subjective feelings are negative feelings, so they may not be fully independent.

There was a significant inverse correlation between age and play duration, whereby older participants could comfortably play the game for shorter durations. A potential explanation is that play duration may also relate to participants' level of interest in playing the game. The older participants had more years of previous gaming experience (significant correlation between age and years of game experience $r = 0.33$, $p = 0.02$); the younger participants may have been more interested in playing the game for longer time.

A potential concern relating to HMDs is whether people with frame glasses can wear the device comfortably. In the current study, we found that participants who wore frame glasses could use the VR-HMD unit with their glasses on, and the results showed that their play duration was not significantly different in comparison to participants who did not wear frame glasses. The HMD unit (Oculus Rift DK2) seems to have enough space to accommodate frame glasses worn by the participants in the current study. Although the participants with frame glasses did not report any incidents, we noticed that the HMD unit may not be able to fit all types of frames, and there is a chance of scratching the lenses on the frame glasses if the HMD unit is pressed too close to the glasses.

Regarding the use of MSAQ for measuring motion sickness, participants only completed the survey after the experiment, as was the case in the original study for which the method was introduced (Gianaros et al. 2001), because MSAQ is designed to measure motion sickness after exposure and is not suitable to measure everyday experience. In addition, participants’ level of motion sickness before game play were expected to be minimal, because the procedures for introduction, informed consent, and ocular measurement took approximately 30 minutes prior to the game play, which should provide enough time for participants to rest.

Based on the observations from the current study, we provide the following recommendations for players. If it is the first time that a player has experienced VR-HMD games, it is recommended to start with less motion in the VR. Players who have no problems with non-HMD video games should avoid being overconfident, because the VR-HMD experience is quite different and seems more likely to cause simulator sickness. In the case of driving simulation, look around the scene first, and then start driving slowly. Avoid sharp turns in the beginning, and gradually increase driving speed. Take short breaks after playing for about 5 minutes, and gradually increase play duration. Longer periods of rest are recommended after continuously playing for about 50 minutes.

Researchers have explored design techniques for reducing motion sickness in VR-HMD games (e.g., Ueda et al. 2018), and there are guidelines for VR game design (Rebenitsch and Owen 2016; Porcino et al. 2017), such as controlling the level of virtual motion and taking break periodically. However, there is a lack of play duration statistics reported in the literature. The question of how long people can comfortably play VR games is important but often neglected. Play duration can affect game enjoyment. But many studies only asked participants to play for a short period of time such as around 10 minutes (Shaw et al. 2015; Yoo et al. 2017). Longer play duration is needed, and the numerical values of comfort play duration are very important because they provide game designers benchmarks to measure design improvement and references to determine the best timing of rest reminders. Parents also need to know suitable play duration for their children. Since this number is affected by factors such as the type of game, many studies are needed to accumulate data in this research field. There are only very limited data available, as we have summarized in Table 3. The current study is a start with one type of game (i.e., car racing). Future work will add more results from other types of games. The methods used in the current study can provide a basis for future studies.

After Study 1 that focused on game play duration in VR-HMD, Study 2 was conducted to compare game play in VR-HMD versus desktop LCD. When the duration of play was held constant (45 minutes) for both conditions, simulator sickness was significantly higher in the VR-HMD condition than the desktop LCD condition. The level of increment from 5.0 to 15.2 on the MSAQ simulator sickness scale (0-100 range) was moderate. While in both conditions, reported eye symptoms slightly increased after playing the game (6.8) in comparison to before playing (4.4) on the CSQ scale (0-50 range), there was no significant difference between the two display conditions. Game engagement and game performance were not significantly different between the two display conditions. These results suggest that the effects of VR-HMD game play (using the driving simulation game) is similar to the effects of using traditional desktop LCD displays, except for a moderately increased level of simulator sickness. For game players and researchers who want to use VR-HMD as a device for driving safety experiments, the current results suggest that it is better to keep the duration of play within a moderate level (within around 45 minutes). Non-HMD displays are recommended for longer duration of play due to smaller concerns about simulator sickness. Note that the results may be specific to this genre of vehicle simulation games where the level of visual motion is moderate, and the driver was not required to frequently scan the entire 360 degrees of the scene. With higher levels of visual motion in a game, such as first-person shooter games and roller coaster games, the simulator sickness issue of VR-HMD may become worse.

In conclusion, we examined how long people could comfortably play a driving simulator game using a commercial VR-HMD continuously without a break (up to 2 hours). We found that the average game play duration was approximately 50 minutes. While large individual differences exist, simulator sickness seems to be an important factor limiting VR-HMD affordable play duration. We also found that age was inversely correlated with game play duration. These findings could help researchers assess the impact of VR-HMD games and inform game designers about the proper duration of game scenarios for driving simulations. VR-HMD game play of the driving simulation game is comparable to that using a traditional desktop LCD display, except for a moderately increased level of simulator sickness. Since there are still very limited empirical data about the impact of VR-HMD on game experience, more studies are needed to further examine other types of games and factors such as repeated exposure and adaptation to simulator sickness.

References

Andre JT, Muth ER, Stern RM, Leibowitz HW (1996) The effect of tilted stripes in an optokinetic drum on gastric myoelectric activity and subjective reports of motion sickness. Aviation, space, and environmental medicine 67:30–33

Badcoe I (2000) The computer game industry: Current state of play. Virtual Reality 5:204–214. doi: 10.1007/BF01408519

Bles W, Bos JE, de Graaf B, et al (1998) Motion sickness: only one provocative conflict? Brain Research Bulletin 47:481–487. doi: 10.1016/S0361-9230(98)00115-4

Bridgeman B, Blaesi S, Campusano R (2014) Optical correction reduces simulator sickness in a driving environment. Human Factors: The Journal of the Human Factors and Ergonomics Society 56:1472–1481

Brockmyer JH, Fox CM, Curtiss KA, et al (2009) The development of the Game Engagement Questionnaire: A measure of engagement in video game-playing. Journal of Experimental Social Psychology 45:624–634

Brooks JO, Goodenough RR, Crisler MC, et al (2010) Simulator sickness during driving simulation studies. Accident analysis & prevention 42:788–796

Chaumillon R, Romeas T, Paillard C, et al (2017) The use of transdermal scopolamine to solve methodological issues raised by gender differences in susceptibility to simulator sickness. Transportation research part F: traffic psychology and behaviour 47:42–58

Chen C, Czerwinski M, Macredie R (1998) Human factors in virtual environments. Virtual Reality 3:223–225. doi: 10.1007/BF01408702

Classen S, Bewernitz M, Shechtman O (2011) Driving simulator sickness: An evidence-based review of the literature. American Journal of Occupational Therapy 65:179–188. doi: 10.5014/ajot.2011.000802

Darty K, Saunier J, Sabouret N (2014) Effects of gender on presence and virtual driver perception in driving simulators. In: The 5th International Conference on Women’s Issues in Transportation (WIiT 2014)

Davis J, Animashaun A, Schoenherr E, McDowell K (2008) Evaluation of semi-autonomous convoy driving. Journal of Field Robotics 25:880–897

Davis S, Nesbitt K, Nalivaiko E (2015) Comparing the onset of cybersickness using the Oculus Rift and two virtual roller coasters. In: Proceedings of the 11th Australasian Conference on Interactive Entertainment (IE 2015). p 30

Domeyer JE, Cassavaugh ND, Backs RW (2013) The use of adaptation to reduce simulator sickness in driving assessment and research. Accident Analysis & Prevention 53:127–132. doi: 10.1016/j.aap.2012.12.039

Ebenholtz SM (1992) Motion sickness and oculomotor systems in virtual environments. Presence: Teleoper Virtual Environ 1:302–305. doi: 10.1162/pres.1992.1.3.302

Gálvez-García G, Hay M, Gabaude C (2015) Alleviating simulator sickness with galvanic cutaneous stimulation. Human factors 57:649–657

Gianaros PJ, Muth ER, Mordkoff JT, et al (2001) A questionnaire for the assessment of the multiple dimensions of motion sickness. Aviation, space, and environmental medicine 72:115–119

Golding JF (2006) Motion sickness susceptibility. Autonomic Neuroscience 129:67–76

Guo C (2014) Effects of eye motion, foveal retinal slip and peripheral retinal slip on visually induced motion sickness. Thesis Ph.D., Hong Kong University of Science and Technology

Häkkinen J, Pölönen M, Takatalo J, Nyman G (2006) Simulator sickness in virtual display gaming: A comparison of stereoscopic and non-stereoscopic situations. In: Proceedings of the 8th Conference on Human-computer Interaction with Mobile Devices and Services. ACM, New York, NY, USA, pp 227–230

Hamel J, De Beukelear S, Kraft A, et al (2013) Age-related changes in visual exploratory behavior in a natural scene setting. Frontiers in psychology 4:339

Helland A, Lydersen S, Lervåg L-E, et al (2016) Driving simulator sickness: Impact on driving performance, influence of blood alcohol concentration, and effect of repeated simulator exposures. Accident Analysis & Prevention 94:180–187. doi: 10.1016/j.aap.2016.05.008

Hettinger LJ, Riccio GE (1992) Visually induced motion sickness in virtual environments. Presence: Teleoperators & Virtual Environments 1:306–310

Howarth PA, Costello PJ (1997) The occurrence of virtual simulation sickness symptoms when an {HMD} was used as a personal viewing system. Displays 18:107–116. doi: http://dx.doi.org/10.1016/S0141-9382(97)00011-5

Hu S, Stern RM, Vasey MW, Koch KL (1989) Motion sickness and gastric myoelectric activity as a function of speed of rotation of a circular vection drum. Aviation, space, and environmental medicine

Jäger M, Gruber N, Müri R, et al (2014) Manipulations to reduce simulator-related transient adverse health effects during simulated driving. Medical & biological engineering & computing 52:601–610

Karl I, Berg G, Ruger F, Farber B (2013) Driving behavior and simulator sickness while driving the Vehicle in the Loop: Validation of longitudinal driving behavior. IEEE Intelligent Transportation Systems Magazine 5:42–57. doi: 10.1109/MITS.2012.2217995

Kennedy RS, Lane NE, Berbaum KS, Lilienthal MG (1993) Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. The International Journal of Aviation Psychology 3:203–220. doi: 10.1207/s15327108ijap0303_3

Kennedy RS, Stanney KM, Dunlap WP (2000) Duration and exposure to virtual environments: Sickness curves during and across sessions. Presence: Teleoperators and virtual environments 9:463–472

Keshavarz B, Novak AC, Hettinger LJ, et al (2017) Passive restraint reduces visually induced motion sickness in older adults. Journal of Experimental Psychology: Applied 23:85–99. doi: 10.1037/xap0000107

Kolasinski EM (1995) Simulator Sickness in Virtual Environments. DTIC Document

Koslucher F, Haaland E, Stoffregen TA (2016) Sex differences in visual performance and postural sway precede sex differences in visually induced motion sickness. Experimental brain research 234:313–322

Kosunen I, Salminen M, Järvelä S, et al (2016) RelaWorld: neuroadaptive and immersive virtual reality meditation system. In: Proceedings of the 21st International Conference on Intelligent User Interfaces. ACM, pp 208–217

Lin J-W, Duh HB-L, Parker DE, et al (2002) Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In: Virtual Reality, 2002. Proceedings. IEEE. IEEE, pp 164–171

McCaffrey RJ, Graham G (1980) Age-related differences for motion sickness in the rat. Experimental aging research 6:555–561

McMahan RP, Bowman DA, Zielinski DJ, Brady RB (2012) Evaluating display fidelity and interaction fidelity in a virtual reality game. IEEE Transactions on Visualization and Computer Graphics 18:626–633

Merhi O, Faugloire E, Flanagan M, Stoffregen TA (2007) Motion sickness, console video games, and head-mounted displays. Human Factors 49:920–934

Miyazaki J, Yamamoto H, Ichimura Y, et al (2015) Inter-hemispheric desynchronization of the human MT+ during visually induced motion sickness. Experimental Brain Research 233:2421–2431. doi: 10.1007/s00221-015-4312-y

Moss JD, Muth ER (2011) Characteristics of head-mounted displays and their effects on simulator sickness. Human factors 53:308–319

Neumann DL, Moffitt RL, Thomas PR, et al (2017) A systematic review of the application of interactive virtual reality to sport. Virtual Reality. doi: 10.1007/s10055-017-0320-5

Palmisano S, Mursic R, Kim J (2017) Vection and cybersickness generated by head-and-display motion in the Oculus Rift. Displays 46:1–8

Patterson R, Winterbottom MD, Pierce BJ (2006) Perceptual issues in the use of head-mounted visual displays. Human factors 48:555–573

Porcino TM, Clua E, Trevisan D, et al (2017) Minimizing cyber sickness in head mounted display systems: design guidelines and applications. In: Serious Games and Applications for Health (SeGAH), 2017 IEEE 5th International Conference on. IEEE, pp 1–6

Rau P-LP, Peng S-Y, Yang C-C (2006) Time distortion for expert and novice online game players. CyberPsychology & Behavior 9:396–403

Rebenitsch L, Owen C (2016) Review on cybersickness in applications and visual displays. Virtual Reality 20:101–125. doi: 10.1007/s10055-016-0285-9

Riccio GE, Stoffregen TA (1991) An ecological theory of motion sickness and postural instability. Ecological Psychology 3:195–240. doi: 10.1207/s15326969eco0303_2

Rosenfield M (2011) Computer vision syndrome: A review of ocular causes and potential treatments. Ophthalmic and Physiological Optics 31:502–515. doi: 10.1111/j.1475-1313.2011.00834.x

Schell J (2014) The Art of Game Design: A book of lenses. CRC Press

Shafer DM, Carbonara CP, Korpi MF (2018) Factors Affecting Enjoyment of Virtual Reality Games: A Comparison Involving Consumer-Grade Virtual Reality Technology. Games for health journal

Shaw LA, Wünsche BC, Lutteroth C, et al (2015) Development and evaluation of an exercycle game using immersive technologies. Australian Computer Science Communications 37:75–85

Situ P, Simpson T, Chalmers R, et al (2013) Validation of the Current Symptoms Questionnaire (CSQ): a meta-analytical approach. Investigative Ophthalmology & Visual Science 54:6023–6023

Stanney KM, Kennedy RS, Drexler JM, Harm DL (1999) Motion sickness and proprioceptive aftereffects following virtual environment exposure. Applied ergonomics 30:27–38

Treisman M (1977) Motion sickness: An evolutionary hypothesis. Science 197:493–495

Ueda Y, Nagata K, Masuko S, Hoshino J (2018) Reorientation Method to Suppress Simulator Sickness in Home VR Contents Using HMD. In: International Conference on Entertainment Computing. Springer, pp 228–234

Yoo S, Heywood T, Tang LM, et al (2017) Towards a Long Term Model of Virtual Reality Exergame Exertion. In: Proceedings of the 25th Conference on User Modeling, Adaptation and Personalization. ACM, pp 247–255