Transportation Research Part F 78 (2021) 180–193

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Driving simulation sickness and the sense of presence: Correlation and contributing factors

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A R T I C L E I N F O

Article history:
Received 23 September 2020
Received in revised form 27 January 2021
Accepted 8 February 2021
Available online 3 March 2021

Keywords:
Driving simulator
Motion sickness
Presence
Speed
Roadway environment
Simulator sickness

A B S T R A C T

Driving simulators are useful and effective tools for conducting studies in the field of traffic safety. Simulation sickness (SS) and the sense of presence (SP) are two well-known factors that could affect the results of the driving simulator experiments. This study investigated the relationship between SP and SS in a medium-fidelity driving simulator. Additionally, the impact of the road environment (urban arterials or rural expressways) on these subscales was investigated. Data was collected by means of self-reported questionnaires, which were conducted after the participants have driven the simulation scenarios in a fixed-base medium-fidelity driving simulator. A total of 125 drivers participated in this study. Results showed that females reported significantly higher SS scores than males. An increasing trend in the SS was observed with the increase of age. Importantly, designing buildings that replicate a real-world environment could increase SP and decrease SS. Moreover, designing high quality and resolution scenarios could also increase SP, thus decreasing the severity of SS symptoms. The results of this study can help researchers using medium-fidelity driving simulators to know the influencing factors for each subscale of SP on SS. Adjustments in the driving simulator and scenario settings as well as additional training exercises for higher speed scenarios can be beneficial in reducing the severity of SS.

1. Introduction

1.1. Background

Simulation-based studies contribute numerously to scientific and industrial research on driving behavior. Driving simulators are used as a useful tool in traffic safety (Pinto, Cavallo, & Ohlmann, 2008). They offer the opportunity for researchers to test different driving situations in a controlled and safe environment. This includes testing near-crash events with no real crash risks compared to performing the same task in the real-world environment, such as driving under the influence of alcohol (Mets et al., 2011; van Dijken et al., 2020; Yadav & Velaga, 2019), driving in adverse weather conditions (Chen et al., 2019) and driving while using mobile phones (Benedetto, Calvi, & D'Amico, 2012; Papadakaki, Tzamalouka, Gnardellis,

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https://doi.org/10.1016/j.trf.2021.02.005
1369-8478/

Lajunen, & Chliaoutakis, 2016; Törnros & Bolling, 2006). Moreover, researchers can study the efficiency of new countermeasures before the real-world implementation, such as variable message signs (Dutta, Fisher, & Noyce, 2004; Reinolsmann et al., 2019a, 2019b; Xu, Wu, Rong, & Peng, 2020), intelligent transportation system ITS-based technologies (Aramrattana, Andersson, Reichenberg, Mellegård, & Burden, 2019; Hussain, Alhajyaseen, Brijs, Pirdavani, & Brijs, 2020a,b; Larue, Rakotonirainy, Haworth, & Darvell, 2015) and in-vehicle or connected environment (Yang, Ahmed, & Subedi, 2020), etc.

Like other apparatuses, there are certain limitations for driving simulator studies. One of the main concerns is the validation of a driving simulator, i.e., to ensure the accuracy of data collected from it in comparison to the real world (Blaauw, 1982; Llorca & Farah, 2016). According to (Grácio, Wentink, Valente Pais, Van Paassen, & Mulder, 2011), driving behavior could be influenced due to the type of simulators. Compared to the fixed-base simulators, motion-base simulators could produce more accurate results for advanced driving maneuvers (such as the accuracy of lateral position while driving for sharp curves). However, in the case of simulation sickness (SS), research indicates that it still remains an important issue regardless of the technological developments in the field of virtual reality presentation in the last few decades (Duzmanska, Strojny, & Strojny, 2018). According to Klüver, Herrigel, Preuß, Schöner, and Hecht (2015), compared to the level of fidelity of simulators, user and scenario characteristics could be more effective in terms of overcoming SS severity. The SS, also known as simulation adaptation syndrome (SAS), is a specific form of motion sickness (Keshavarz, Ramkhalawansingh, Haycock, Shahab, & Campos, 2018; Lucas, Kemeny, Paillot, & Colombet, 2020). It is experienced when a discrepancy occurs between the visual and vestibular systems (e.g., sense of balance and spatial orientation). This phenomenon can be described as "vection" and is also associated with the well-known train movement illusion, which produces the illusion of moving if, instead, the surrounding train is moving. In virtual worlds and simulators, vection can also easily occur (Hettinger, Schmidt, Jones, & Keshavarz, 2014). Several hypotheses and theories were suggested to describe the occurrence of motion and SS. An important explanation was provided by Reason and Brand (1975), who introduced the Sensory Conflict Theory. According to this theory, a conflict between the visual sense, the vestibular sense (balance and spatial orientation), and body awareness (proprioception) can occur if the drivers' perception in the simulator differs with expectations based on previous driving experiences. This means if the sensory information intake deviates from the expected sensory information, SS is likely to occur. The subjective theory of vertical conflict can be interpreted as a simplification of the idea of sensory conflicts with a focus on postural instability. According to the subject vertical-conflict theory, only one conflict exists between the perceived and expected incoming sensory signals when moving, which increases motion sickness (Bles, Bos, De Graaf, Groen, & Wertheim, 1998). On the other hand, there is also visually induced motion sickness, which is a somewhat similar to conventional motion sickness, however with minimal or absent physical movements. The common symptoms are oculomotor disturbances and disorientation. Moreover, the theory of eye movement describes that the vagus nerve is affected through tension in the eye muscles when visual stimuli are moving quickly, leading to headache, eye strain and visual tiredness (Keshavarz, Riecke, Hettinger, & Campos, 2015). Also, the SS occurs when the visual system of the human detects movement, however, the movement is not detected by the vestibular system. The primary symptoms of SS include nausea, eye strain, cold sweat, fatigue, dizziness, and vomiting in some severe cases (Classen, Bewernitz, & Shechtman, 2011; Keshavarz et al., 2018; Reinhard et al., 2017). The SS and the sense of presence (SP) in the simulator, that participants experience could contribute to a bias in the collected data (Kim & Park, 2020). The SP can be defined as the subjective experience of being in a VE even though the person is not physically present in that environment (Witmer & Singer, 1998). The quality of the simulated environment can be determined to the extent to which the participant feels being present in the virtual world (Draper, Kaber, & Usher, 1998). Presence consists of two main components, which are involvement and immersion. Involvement is achieved when someone is only focusing on the virtual environment (VE) due to receiving continuous visual stimuli. In contrast, immersion is achieved when someone feels that he is being included and acting within a specific environment (Witmer & Singer, 1998).

Subjective approaches by means of questionnaires are mostly used to measure SS and SP. The simulation sickness questionnaire (SSQ) developed by Kennedy, Lane, Berbaum, and Lilienthal (1993) is the most used in the literature for evaluating the SS. The SSQ focuses on three subscales (i.e., nausea, oculomotor disturbance, and disorientation). Nausea is referring to symptoms such as sweating, difficulty concentrating, and stomach awareness. Oculomotor disturbance refers to headache, eyestrain, and blurred vision, whereas disorientation includes symptoms such as head fullness, dizziness with open and closed eyes, and vertigo (Duzmanska et al., 2018). On the other hand, the presence questionnaire (PQ) developed by Schubert, Friedmann, and Regenbrecht (2001) contains three subscales, which are spatial presence, involvement, and realness, to distinguish between the presence and attentive components. The PQ subscale items are discussed further in the "Methods" section of this paper.

1.2. Related works

It has been reported that demographic factors (i.e., age and gender) can have an impact on SS. The literature showed that age and SS are positively correlated (Allen, Park, Fiorentino, Rosenthal, & Cook, 2006; Kawano et al., 2012; Keshavarz et al., 2018; Schweig, Liebherr, Schramm, Brand, & Maas, 2018). In these studies, age was categorized into two age groups only (i.e., young and old drivers), in which the first group consisted of participants with an age range to 35 or 50 years, while the second age group consisted of participants being older than 50, including elderly people above 65 years. Although Liu, Watson, and Miyazaki (1999) had three age groups (i.e., less than 36, 36–55, and 56+ years), participants in the younger age group did not have a driving license. Similar to the other studies, age and SS were positively correlated in their study.

Regarding gender, Garcia, Baldwin, and Dworsky (2010) have found that females are more susceptible to SS than males. The results were based on a total of 16 participants (8 males and 8 females) using a driving simulator. Another driving simulator study by Rizzo, Sheffield, Stierman, and Dawson (2005) reporting discomfort scores by using a simulator adaptation questionnaire (SAQ), which was developed based on the SSQ and motion sickness questionnaire, showed that females had higher discomfort scores than males. Park, Allen, Fiorentino, Rosenthal, and Cook (2006) studied a large sample of 118 participants with a basic driving simulator having three small monitors with no vehicle cockpit and found that females reported higher SS scores for nausea and oculomotor subscales. Besides age and gender, the symptoms and severity of SS can also depend on the individual proneness, the enjoyment or aversion of interaction with the virtual reality, as well as the characteristics of the simulator itself (Duzmanska et al., 2018). Lin, Duh, Parker, Abi-Rached, and Furness (2002) studied the effects of the field-of-view (FOV) in a real car driving simulator with three large screens on SP, enjoyment, memory, and SS. Ten participants filled in the SSQ, and the FOVs were varied on four levels (60°, 100°, 140°, and 180°). The results showed that SS was positively correlated with SP while it was negatively correlated with "enjoyment" while FOV was increased up to 140°. This means that SS symptoms would decrease due to greater involvement and experienced excitement in a highly interactive VE.

Other virtual reality studies unrelated to driving confirm that SP and SS are inversely correlated. Researchers reported that an increase in SP would result in a decrease in the SS scores (Jerome, Darnell, Oakley, & Pepe, 2005; Witmer & Singer, 1998). The results of these studies reported a general trend without mentioning SS and SP subscales. Nichols, Haldane, and Wilson (2000) studied the correlation between these subscales in a VE study where participants were required to explore several rooms in a virtual house. Twenty participants were recruited for the experiment. Only one subscale (i.e., interface quality) from the PQ was found to have a significant negative correlation with the three SSQ subscales (i.e., nausea, oculomotor, and disorientation).

Using a flight simulator, Kim and Park (2020) investigated the effect of the display type (i.e., flat LCD screens and head-mounted display (HMD)) and the complexity of the scenarios on 'participants' SS and SP. A total of 18 subjects participated in the experiment. Results showed that an LCD screen showed significantly lower SS scores for the total score and the three subscales (i.e., nausea, oculomotor disturbance, and disorientation). On the other hand, sensory and realism factors of the PQ showed significantly higher scores for the HMD. The effect of task complexity was not significant on SS and SP.

Few studies have addressed the relationship between the road environment and the SS. Mourant, Rengarajan, Cox, Lin, and Jaeger (2007) reported in a driving simulator study with 16 participants that driving on straight roads in a rural environment generates lower SS scores than driving in a city environment, which requires making right and left turns. The authors used mini-SSQ, which consists of 6 items only. Park et al. (2006) found that dropout rates of participants increased in scenarios requiring driving at high speeds (i.e., above 70 kph) within a visually complex environment and turning maneuvers at intersections. Regardless of the driving environment, Min et al. (2006) found that the total SS score increases as the driving speed increase from 30 kph to 90 kph or 120 kph. The study was conducted using a low-fidelity driving simulator having a projector and one flat screen. The authors reported the total SS score without considering the three subscales (i.e., nausea, oculomotor disturbance, and disorientation).

To the best of our knowledge, the correlations between SSQ subscales and PQ subscales and their linkage to the road environment (i.e., rural expressway and urban roadway) have not been investigated yet. Also, studies for the Arab countries, including Gulf States that target the same issues, have not been found in the literature. The state of Qatar is a unique case in terms of the diverse driving population, which is characterized by very high diversity in terms of various ethnicities and cultural backgrounds (Soliman, Alhajyaseen, Alfar, & Alkaabi, 2018; Timmermans et al., 2019, 2020). In this regard, previous research indicates that these factors could induce different driving behavior, such as speed and acceleration maneuvers (Almallah, Alfahel, Hussain, Alhajyaseen, & Dias, 2020; Hussain et al., 2019a). Therefore, different cultural backgrounds can also be considered an important parameter in studying SS and SP.

Based on the above discussion, important gaps that can be identified in the literature include (1) the relationship between SS subscales (i.e., nausea, oculomotor disturbance, and disorientation) and SP subscales (i.e., spatial presence, involvement, and realness), (2) the linkage between socio-demographic characteristics and subscales of SS, (3) the correlation between road environment with subscales of SS and SP and (4) analyses of specific countries with multi-cultural driving population, among which the state of Qatar. This paper aims to address these gaps in knowledge and to propose important implications for medium-fidelity driving simulators.

1.3. Study objectives

Fig. 1 presents the overall framework of this study, including the SS and SP. As illustrated in Fig. 1, the study aims to investigate the correlation between SS and SP and their subscales in the simulation environment. In addition, the study also investigates the impact of the road environment on SS and SP. Finally, the study also focuses on relating demographic characteristics to the SS.

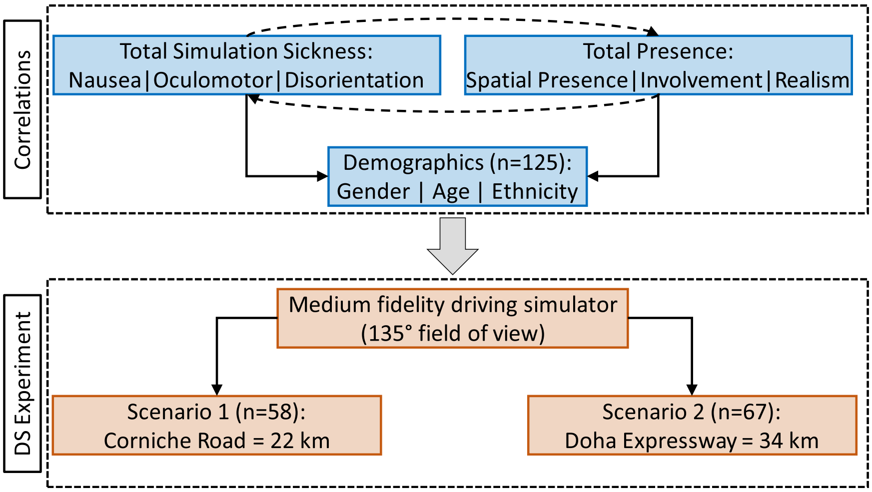


Fig. 1. Framework of the study.

2. Methods

2.1. Driving simulator

The simulator used in this study is a fixed-base medium-fidelity driving simulator located at Qatar Transportation and Traffic Safety Center at the College of Engineering of Qatar University (Fig. 2). The simulator consists of three large LCD monitors having a resolution of 5760 × 1080 pixels and a 60 Hz refresh rate with a FOV of 135°. The wing and rear-view mirrors are displayed on the simulation screens with appropriate positions. Moreover, the driving simulator contains a cockpit of the real Range Rover Evoque in which the mechanical parts that are unnecessary are replaced with electronic systems, which are connected to a workstation. Force-feedback steering wheel, accelerator, and brake pedals are used to control drivers' feedback. Other functional tools of the simulator include the automatic gearbox, indicators, a speedometer, and a tachometer. These components are interfaced with STISIM Drive® 3, which is a product of Systems Technology, Incorporated (STI) and the CalPot32 program, which offers high-speed graphics and sound processing (Eriksson, de Winter, & Stanton, 2018). The system is capable of producing proper engine and road noise, which is transmitted through the simulation auditory system. In previous studies, the simulator has been validated subjectively, and objectively for actual speed and speed perception (Hussain et al., 2019b), and geometric field of view (GFOV) (Hussain, Almallah, Alhajyaseen, & Dias, 2020c).

2.2. Road environment

In this study, data was collected for two scenarios representing two road environments (i.e., urban roadway and rural expressway), as shown in Fig. 3. The study was designed as a between-subject, meaning that some participants (n = 58) drove on the urban roadway while others drove on the rural expressway (n = 67). More information regarding the demo-

Fig. 2. Driving simulator at Qatar University.


a) Rural Environment b) Urban Environment

Fig. 3. Simulated road environments – rural vs urban.

graphic proportions of each sample is provided in Section 2.5 "Participants". The between-subject design was chosen for this study to eliminate learning effects.

The first environment representing an urban view simulated the 'Corniche' road located in the downtown of Doha city (Fig. 3b). This was characterized by three driving lanes for each direction, several signalized intersections, 80 km/h posted speed limit, medium traffic, and many tall buildings along the road. Participants were instructed to drive only straight without making any turn at intersections. The second environment represents a rural expressway that connects Doha city to the North of Qatar (Fig. 3b). The rural part of the expressway is characterized by four driving lanes per direction, 120 km/h posted speed limit, low to medium traffic, and a few buildings in the desert environment. Lane width for both road environments was 3.65 m, while the median width was 7 m and 4 m for rural and urban environments, respectively. Regarding the road alignment, the urban and the rural road environments were designed with similar horizontal (i.e., very smooth curves) and vertical alignments (i.e., level road).

The vehicle composition in the driving scenarios was based on real-world observations which consist of 45.7% SUVs, 47.8% sedan passenger cars, and 6.5% other vehicles (i.e. buses and vans). In both road environments, the design was replicating the real-world environment in terms of buildings, roadside elements (i.e. streetlights and trees), and geometrical alignment. All buildings and roadside elements were designed using SketchUp Pro (version 18.0.16975) (Yang, Yan, Guo, & Lin, 2013; Zekar & Khatib, 2018).

2.3. Simulation sickness and presence measurement

In this study, SS and SP were evaluated subjectively by means of SSQ developed by Kennedy et al. (1993) and PQ by Schubert et al. (2001). The SSQ consists of 16 items representing symptoms divided into three subscales (i.e., nausea, oculomotor disturbance, and disorientation). Each subscale contains 7 items, of which some items are included in two subscales. The severity of each item is measured using a four-point scale (i.e., 0 represents no symptom, and 3 represents the highest severity of the symptom).

The questions associated with PQ were designed as 7-point Likert scales. The PQ consists of three subscales (i.e. spatial presence, involvement, and realness). Items of spatial presence (N = 6 items) describe the classic definition of presence which is the feeling of being present in the VE such as the sense of acting in the VE as compared to feeling unconnected (not present) to the observed VE. Involvement items (N = 4 items) describe that state of being attentive to the VE and the possible distraction from the real-world environment. For example, some items for this subscale ask if the participant was captivated by the VE and if participants were still aware of the real environment. The realness items (N = 3 items) are comparing the perceived consistency of the virtual versus the real-world environment. For example, some items ask about how real the VE was compared to the real environment and about the perceived consistency of experiencing the VE.

2.4. Procedures

The recruitment process was started by emailing Qatar University-affiliated people as the first goal society and continued by posting a notification spread via social media platforms to include drivers from outside of the campus. All subjects registered in the experiment through an official website (http://www.qatardrivingsimulator.com). Upon arrival, each participant was given a brief introduction about the driving simulator. Then, all participants were asked to sign an informed consent form containing information about SS and 'participants' right to quit the experiment for any reason and at any time. In addition, we confirmed the physiological state of the participants by verbally asking if they were feeling well and were ready to participate in the experiment. A pre-test questionnaire was completed by the participants to collect demographics (e.g., age, gender, and nationality). After completing the pre-test questionnaire, participants were given at least a 5 min practice drive to make sure that they get familiarized with the driving simulator (Underwood, 2005). The experimental drives were started after confirmation from the participants. The participants were instructed to drive as they would normally drive on the real roads and to follow the traffic rules. Participants were also informed that the speed limit is 80 km/h for those who drove in the urban environment and 120 km/h for those subjects who drove on the rural expressway. The duration of each test drive was approximately 25 min. After completing the test drive, the participants were requested to fill in the SSQ, followed by the PQ using the online platform named Qualtrics. The SSQ and the PQ took around 5 min each to be completed. The average duration of completing one test drive and the pre & post questionnaires was approximately 50 min.

2.5. Participants

A total of 132 subjects holding a valid Qatari driving license participated voluntarily in the experiment (61 drove the experiment for the urban arterial while 71 for the rural expressway). In line with the minimum requirements of SSQ (Kennedy et al., 1993), all the participants were informed in advance not to drink (except water) or eat two hours prior to the experiment. Regardless of the provided information, seven subjects (3 for urban arterial while 4 for rural expressway) were affected due to SS in the early stages of the experiment, and therefore, were not eligible to fill in SSQ and PQ and removed from the results. Thus, data from 125 participants were used for the analyses. The demographic characteristics of 125 drivers (58 for urban while 67 for rural) and the actual population of Qatar (Planning and Statistics Authority, 2018, 2019) are summarized in Table 1. The table includes percentages of the demographic characteristics for each scenario separately (i.e., Urban sample vs. Rural sample), total sample, and actual population. The final sample was composed of 67.8% male and 32.2% female subjects. Regarding the age groups, 36.1% were between 18 and 25 years, 55.8% were between 26 and 45 years, while 8.1% were older than 45 years. When it comes to ethnicity, 51% of the total participants were Arabs, 32.9% were Asians or Africans, while 16.1% were Westerners.

2.6. Analysis

The data collected in the three questionnaires (i.e., pre-test questionnaire, SSQ, and PQ) was further analyzed with SPSS statistics 26 and Minitab 17 software. The data of age, gender, and nationality was extracted from the pre-test questionnaire. Participants were categorized into three age groups (i.e., 18–30, 31–45, and 45+ years old) to get more nuanced insights into the age distribution of drivers in Qatar (Soliman et al., 2018). For nationality, the analysis was based on three groups of origin (i.e., Asian, Africans, and Westerners). The Westerners group included nationalities from Europe, New Zealand, the US, and Canada.

For SSQ, the score of each subscale was calculated by summing the scores of items that belong to each subscale and multiplying the obtained sum by the specific weight (i.e., 9.54 for nausea, 7.58 for oculomotor disturbance, and 13.92 for disorientation) as described in Kennedy et al. (1993). For PQ, items for each subscale (i.e., spatial presence, involvement, and realness) were grouped, and the sum was calculated for each group.

To investigate the relationship of SS subscales with the demographic factors, we followed non-parametric tests. Non-parametric tests were used due to the fact that data was based on the subjective scores, and the SS scores were skewed more towards the lower bound (Sánchez, Sahker, & Arndt, 2020). In this regard, Kruskal-Wallis tests were used to estimate the probabilistic values of the SS subscales for each demographic factor. The Kruskal Wallis test is a non-parametric method that does not require the normal distribution assumption (Bajaj, Taran, Khare, & Sengur, 2020). In addition, to assess the relationships between SS subscales and SP subscales and their linkage to the road environment, Spearman's correlations were applied. Similar to Kruskal-Wallis tests, Spearman's correlation test also does not require the assumption of normal distribution (Hauke & Kossowski, 2011).

Table 1
Demographic characteristics of the participants.

Variable	Levels	Sample (Urban)	Sample (Rural)	Total sample	Population[a]
Gender	Male	75.9%	59.7%	67.8%	74.2%
	Female	24.1%	40.3%	32.2%	25.8%
Age groups	18–25 years	36.2%	35.9%	36.1%	15.5%
	26–35 years	48.3%	37.5%	42.9%	40.8%
	36–45 years	10.3%	15.6%	12.9%	27.0%
	>45 years	5.2%	10.9%	8.1%	11.5%
Ethnicity	Arabs	48.3%	53.7%	51%	9% Qatari[b]
	Asians/Africans	44.8%	20.9%	32.9%	AND
	Westerners	6.9%	25.4%	16.1%	91% other nationalities[c]

[a] Demographic characteristics of the population in the state of Qatar (Planning and Statistics Authority, 2018, 2019).
[b] Based on the population of 15 years of age and above.
[c] Includes labors that are not eligible for possessing a driving license.

3. Results

3.1. Analysis of demographic factors

In order to investigate significant differences between SS subscales' scores and demographic factors of the participants, Kruskal Wallis test was estimated separately for each factor (see Table 2). Results showed that there were significant differences between males and females' mean ranks for Oculomotor (Kruskal-Wallis χ^2 = 4.04, p = 0.04) and Disorientation (Kruskal-Wallis χ^2 = 4.60, p = 0.03) scores. In this regard, higher mean rank values were observed for females compared to males in both cases (i.e., Oculomotor and Disorientation). This indicates that Oculomotor and Disorientation symptoms were significantly higher in females. In addition, the mean ranks for Nausea scores were found to be significant for the age groups (Kruskal-Wallis χ^2 = 8.40, p = 0.01) and ethnicity groups (Kruskal-Wallis χ^2 = 6.36, p = 0.04), indicating that nausea symptoms were significantly different between the three age groups and between the three ethnicity groups. The mean rank values were found to be 60.2, 60.6, and 75.1 for the age groups of 18–30, 31–45, and >45 years, respectively. On the other hand, the mean rank values for Asians, Africans, and Westerners were 61.7, 58.7, and 74.8, respectively.

The effects that were significant in Kruskal-Wallis tests are plotted as boxplots for each demographic factor separately (see Fig. 4). It can be seen from Fig. 4(a) that female drivers reported significantly higher SS for oculomotor and disorientation compared to male drivers. The mean oculomotor and disorientation scores for females were 40.11 and 63.83, which were higher than the male group, i.e., 31.13 and 43.25, respectively. Fig. 4(b) illustrates the boxplots and mean nausea scores for each age group. It can be read from the figure that the highest mean nausea score (Mean: 49.61) was reported by the eldest group compared to the other groups. Regarding the "Ethnicity", Westerners reported the highest nausea score (Mean: 47.22) followed by Africans (Mean: 23.55) and Asians (Mean: 22.34) as shown in Fig. 4 (c). As both "Ethnicity" and "Age groups" were significant for the nausea symptoms, the effects were estimated between the different age groups considering each ethnic group separately. In this regard, separate Kruskal Wallis tests were conducted to estimate nausea scores for "Age groups vs Asians", "Age groups vs Africans", and "Age groups vs Westerners". The results showed no significant difference between the different age groups taken separately for each ethnic group, i.e., Age groups vs Asians (Kruskal-Wallis χ^2 = 0.67, p = 0.71), Age groups vs Africans (Kruskal-Wallis χ^2 = 1.63, p = 0.44) and Age groups vs Westerners (Kruskal-Wallis χ^2 = 0.36, p = 0.84).

3.2. Correlation tests – Road environment vs. SS and SP subscales

Spearman's correlation results for the factor "Road Environment" with the continuous factors are shown in Table 3. Results show positive correlations with the SS subscales and negative correlations with SP subscales. For SS, a significant positive correlation is found for the factors "Nausea" ($r_{(123)}$ = 0.278, p = .002), "Oculomotor" ($r_{(123)}$ = 0.219, p = .014) and "Total sickness" ($r_{(123)}$ = 0.225, p = .012). This means that as the road environment becomes more rural with the higher posted speed limits, nausea, oculomotor disturbance, and total SS scores increased. Regarding SP, the factor "Realism" has a significant negative correlation with the factor "Road Environment" ($r_{(123)}$ = −0.249, p = .005), indicating that SP for the realism subscale decreases for the rural expressway environment and increases as the road environment becomes urban.

Fig. 5 visualizes the differences between SS and SP subscales in terms of both types of road environments. In addition, the mean values of each score and for each road type are presented in the tables within Fig. 5. It can be seen that higher scores were reported in the rural environment for all SS subscales compared to the urban environment (Fig. 5a). On the other hand, the mean scores of each SP subscale were higher for the urban environment compared to the rural environment.

Table 2
Kruskal-Wallis tests (Null hypothesis = The distribution of the SS subscales is the same across the different levels of the demographic factors).

Demographic factors	SS variables	Kruskal-Wallis Test		
		Kruskal-Wallis H	df	*p*
Gender	*Nausea*	3.722	1	0.054
	Oculomotor	4.044	1	**0.044**
	Disorientation	4.603	1	**0.032**
	Total	3.762	1	0.052
Age groups	*Nausea*	8.407	2	**0.015**
	Oculomotor	4.276	2	0.118
	Disorientation	4.497	2	0.106
	Total	3.862	2	0.145
Ethnicity	*Nausea*	6.366	2	**0.041**
	Oculomotor	5.278	2	0.071
	Disorientation	1.876	2	0.391
	Total	1.745	2	0.418

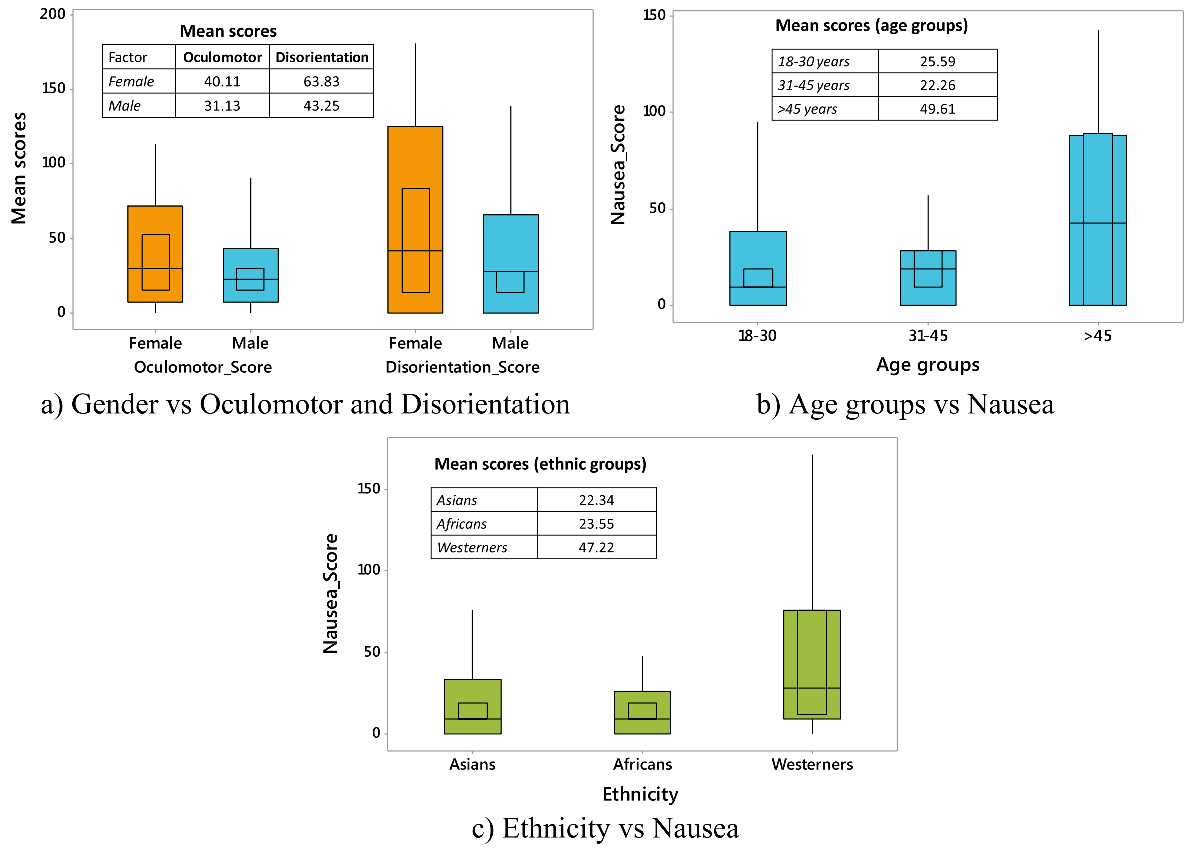


Fig. 4. Boxplots of the significant factors for different demographic factors.

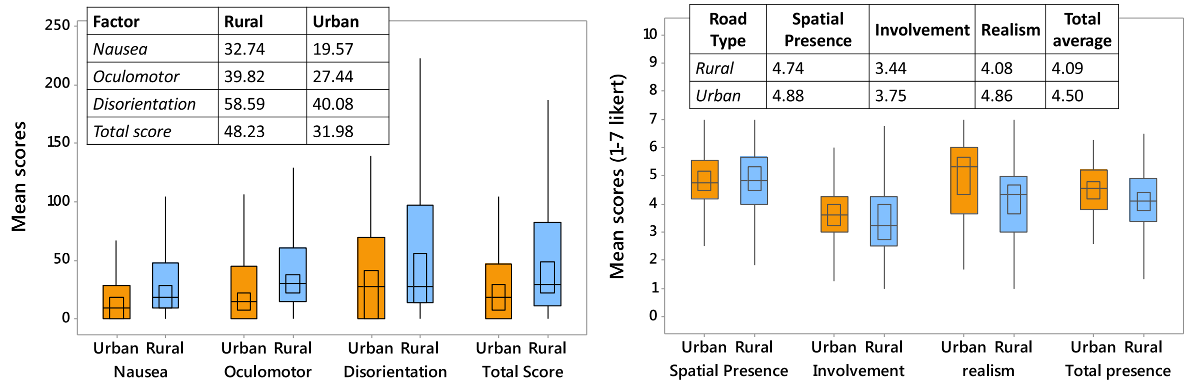
Table 3
Spearman's Correlations of road environment with the SS and presence subscales (significant p-values at 95% confidence level are indicated in bold).

Spearman's Correlations	Road Environment		
Factors	Coefficient	N	p
Road Environment [a]	1.0	125	– –
Nausea	0.278 [**]	125	**0.002**[**]
Oculomotor	0.219[*]	125	**0.014**[*]
Disorientation	0.154	125	0.086
Total sickness	0.225[*]	125	**0.012**[*]
Presence	−0.009	125	0.921
Involvement	−0.138	125	0.125
Realism	−0.249[**]	125	**0.005**[**]
Total Presence	−0.153	125	0.088

[*] Significant at the 0.05 level (2-tailed).
[**] Significant at the 0.01 level (2-tailed).
[a] Reference category: urban roads with the posted speed limit of 80 km/h.

3.3. Correlation matrix of SS subscales and SP subscales

Table 4 presents the results from Spearman's correlation between the scores of SS and SP subscales. The result showed negative correlations between the SS and SP subscales. Spatial presence has a significant negative correlation with the nausea ($r_{(123)} = -0.227$, $p = .011$) and oculomotor ($r_{(123)} = -0.204$, $p = .022$) symptoms. This indicates that as the sense of spatial presence increases, the severity of nausea and oculomotor symptoms decreases. Similar results were found for the realism factor having a significant negative correlation with nausea ($r_{(123)} = -0.299$, $p < .001$) and oculomotor disturbance



a) SS subscales and Road environment b) SP subscales and Road environment

Fig. 5. Boxplots for SS and SP subscales VS. road environments.

Table 4
Spearman's Correlations of SS subscales with SP subscales (significant p-values at 95% confidence level are indicated in bold).

Factors		Simulation Sickness				Sense of Presence			
		Nausea	Oculomotor	Disorientation	Total SS	Spatial Presence	Involvement	Realism	Total SP
Nausea	Spearman's Coefficient	1.00	0.882**	0.924**	– –	−0.227*	−0.167	−0.299**	– –
	N	125	125	125	– –	125	125	125	– –
	P-value	– –	**<0.001**	**<0.001**	– –	**0.011**	0.063	**<0.001**	– –
Oculomotor	Spearman's Coefficient	0.882**	1.00	0.889**	– –	−0.204*	−0.121	−0.259**	– –
	N	125	125	125	– –	125	125	125	– –
	P-value	**<0.001**	– –	**<0.001**	– –	**0.022**	0.179	**0.004**	– –
Disorientation	Coefficient	0.817**	0.889**	1	– –	−0.143	−0.105	−0.126	– –
	N	125	125	125	– –	125	125	125	– –
	P-value	**<0.001**	**<0.001**	– –	– –	0.111	0.246	0.163	– –
Total SS	Spearman's Coefficient	– –	– –	– –	1	– –	– –	– –	−0.247**
	N	– –	– –	– –	125	– –	– –	– –	125
	P-value	– –	– –	– –	– –	– –	– –	– –	**0.006**
Spatial Presence	Spearman's Coefficient	−0.227*	−0.204*	−0.143	– –	1	0.284**	0.617**	– –
	N	125	125	125	– –	125	125	125	– –
	P-value	**0.011**	**0.022**	0.111	– –	– –	**<0.001**	**<0.001**	– –
Involvement	Spearman's Coefficient	−0.167	−0.121	−0.105	– –	0.284**	1	0.299**	– –
	N	125	125	125	– –	125	125	125	– –
	P-value	0.063	0.179	0.246	– –	**<0.001**	– –	**<0.001**	– –
Realism	Spearman's Coefficient	−0.299*	−0.259**	−0.126	– –	0.617**	0.299**	1	– –
	N	125	125	125	– –	125	125	125	– –
	P-value	**<0.001**	**0.004**	0.163	– –	**<0.001**	**<0.001**	– –	– –
Total SP	Spearman's Coefficient	– –	– –	– –	−0.247**	– –	– –	– –	1
	N	– –	– –	– –	125	– –	– –	– –	125
	P-value	– –	– –	– –	**0.006**	– –	– –	– –	– –

[*] Significant at the 0.05 level (2-tailed).
[**] Significant at the 0.01 level (2-tailed).

($r_{(123)} = -0.259$, p = .004). The higher SP for the realism subscale, the lower the severity of nausea and oculomotor symptoms. In General, it was reported that as the score of the total SP increases, the severity of the total SS score decreases significantly ($r_{(123)} = -0.247$, p = .006). Although the involvement subscale has negative correlations with the three SS subscales, none of these correlations was found to be significant at the 0.05 significance level.

Furthermore, the results show strong significant positive correlations between the SS subscales. Nausea symptoms have significantly positive correlations with oculomotor symptoms ($r_{(123)} = 0.882$, p < .001) and disorientation symptoms

($r_{(123)}$ = 0.924, p < .001). Moreover, oculomotor and disorientation symptoms are positively correlated ($r_{(123)}$ = 0.889, p < .001). This indicates that as the severity of symptoms of any SS subscale increases, the severity of symptoms of the other two subscales would increase. On the other hand, significant positive correlations are found for the SP subscales. Spatial presence has a significant positive correlation with involvement ($r_{(123)}$ = 0.284, p < .001) and realism ($r_{(123)}$ = 0.617, p < .001). In addition, a significant positive correlation is reported between involvement and realism ($r_{(123)}$ = 0.299,p < .00 1). This indicates that when SP that participants feel for any subscale increases, SP of the other two subscales would also increase.

4. Discussion

This study aims to investigate the relationship between SS subscales and SP subscales and the influencing factors affecting these subscales. Participants drove a fixed-base medium-fidelity driving simulator, and afterward, data was collected using self-reported questionnaires (i.e., SSQ and PQ) (Kennedy et al., 1993; Schubert et al., 2001).

The results showed that females are more susceptible to SS symptoms than males. More specifically, females reported significantly higher scores for oculomotor disturbance and disorientation compared to males. These results are supported by other studies showing that females reported higher SS scores than males (Garcia et al., 2010; Park et al., 2006). Regarding age, the highest scores were reported by the eldest group of our study (>45 years), compared to the other groups. Several studies have already suggested that older participants are more likely to have SS symptoms than younger participants due to age-related issues with balance as well as slower visual processing abilities (Brooks et al., 2010; Chen & Chan, 2011). Moreover, SS is rather increasing in individuals with longer exposure duration to a simulation (Kennedy, Stanney, & Dunlap, 2000). Interestingly, Westerners reported higher scores for nausea compared to the other ethnic groups. Interesting results were also found for the relationship between road environment and SS subscales. As the number of buildings and infrastructural components increase, together with the decrease in the posted speed limit, the severity of nausea, oculomotor disturbance, and total SS significantly decreased. There could be two possible explanations for these findings: a) driving at higher traveling speeds in the simulation environment could increase the risk of SS; b) simulation environment that is designed with a low number of buildings located far from the 'drivers' FOV (e.g., rural expressway environment) could increase the chance of potential discrepancies between the visual and vestibular systems and therefore could increase the risk of SS. The former can be explained due to the fact that in the rural environment, the speed limit was 120 km/h compared to 80 km/h for the urban environment. Most participants were driving within the allowed speed limits. This indicates that as drivers drive at higher speed, there is a high chance that the severity of SS symptoms increases. This is in line with other studies indicating that SS increase as drivers travel at higher speeds (Min et al., 2006; Park et al., 2006). The latter occurred when the human visual system detects fast movement, however, due to insufficient visual information, the human vestibular system does not detect the movement.

On the other hand, results revealed that SP for the realism subscale significantly increased for the urban environment with a lower posted speed limit. Many tall buildings were placed closely along the roadway in the urban environment, which also represented typical landmarks on the real Corniche road. Keshavarz et al. (2015) have highlighted that a sophisticated visual environment can introduce the impression of illusory self-motion without creating a sensory conflict. Higher involvement in the VE as in the case of the simulated urban environment is expected to reduce the occurrence of SS. Besides no additional accelerations were simulated in the fixed base simulator, preventing a potential mismatch between the vestibular and the visual system (Keshavarz et al., 2015).

Moreover, the realism subscale includes items that focus on how real the VE appeared to the driver compared to the real-world environment (Schubert et al., 2001). This means that in order to improve realism, participants should feel that they are driving on a road that looks similar to the real road. The easiest way to do this is that buildings and other infrastructure elements in the scenario should be properly designed taken from the real-world environment. Moreover, SP decreases under higher driving speeds on a wide rural expressway since desert buildings in the far environment are less likely to serve as reference objects for speed perception as compared to the closer and dense buildings along the urban roadway. A similar observation has been made in the real world and with real-world videotapes, where drivers underestimated their driving speeds on wide roads and overestimated their driving speeds when the roadway appeared narrower (Martens, Comte, & Kaptein, 1997; Wu et al., 2017). Given that none or only slight curves were present in both driving environments and three till four driving lanes with similar lane width were simulated for both roadway types. Therefore, we are able to attribute the changes in SS to the faster moving visual stimuli due to higher driving speeds on the rural expressway and the less complex visual environment for the rural expressway as compared to the urban arterial.

Particularly, females and drivers with little driving experience tended to have higher estimation errors for high speeds compared to lower speeds (Wu et al., 2017). Whether these speed estimation errors also contribute to higher SS scores among the female drivers as well as for age groups with little driving experience on the rural expressways in Qatar has to be investigated in follow-up studies. In line with sensory conflict and visually induced motion sickness theories, SS is more likely to occur if subjects' age increases and due to the individual' susceptibility to SS in a VE (Reinhard et al., 2017). Continuous exposure and training in the simulator are likely to reduce the appearance of SS symptoms (Duzmanska et al., 2018; Reinhard et al., 2017). Besides, an oculomotor exercise prior to viewing the VE has been proposed in the literature to successfully reduce SS symptoms in subjects (Park et al., 2017).

Interestingly, a significant negative correlation was found between the total SP score and total SS score. Spatial presence and realism significantly reduce nausea and oculomotor disturbance. Spatial presence items focus on the basic definition of presence (i.e., the sense of being there). Participants should feel that they are not only observing the virtual scene, but they should also have the feeling that they are being inside the VE and acting within this environment. One possible solution to increase the spatial presence could be the high quality and resolution of the designed simulation scenarios (Slater & Usoh, 1993). The involvement subscale includes items that focus on how participants were attentive to the VE (Schubert et al., 2001). Although the involvement subscale had negative correlations with the three SS subscales, these correlations were not significant. This could be because the experiment was conducted in a well-isolated simulation room, air-conditioned to 19–20 degrees, and with no other sounds coming from the external environment during the experiment. The results indicate that having minimal distracting noises could help in isolating the participant from the external environment and could increase the degree of involvement in the simulation while reducing the risk of SS.

5. Limitations and future research

It is essential to highlight that there are certain limitations associated with this study. The study was carried out using a static driving simulator, which could have affected the degree of realism. The results for SP may vary for simulators with different level of fidelity. However, in case of SS, certain discrepancies can be observed in the literature while comparing different simulators. For instance, Klüver et al. (2015) found a marginal reduction in SS scores for adequately calibrated and validated moving base simulators compared to static simulators. Another study found no significant difference between SS scores obtained from static vs moving based simulators (Rangelova, Rehm, Diefenbach, Motus, & André, 2020). From a theoretical point of view, Kemeny, Chardonnet, and Colombet (2020) indicated that advanced moving base simulators (e.g., with 6-axis and/or linear actuators) could help in reproducing human motion perception and overcoming the conflict between visual sense and the vestibular sense. However, another study showed that vertical head movements in the moving base simulators could provoke discomfort, i.e., disorientation, visual sickness and psychophysical situation (Aykent, Merienne, Guillet, Paillot, & Kemeny, 2014). Therefore, future research is needed to empirically investigate the relationships between SS subscales and SP subscales for moving base simulators. In addition, future studies could also include sharp curves including left/right turns at intersections to investigate their impact on the relationship between SS and SP.

Another limitation could be that data was collected between-subjects in terms of different road environments (i.e., rural road vs. urban road). Therefore, this might have produced certain biases in the results due to the individual differences and variability issues in the between-subject tests (MacDougall, Brizuela, Burgess, & Curthoys, 2002). However, the between-subjects design was chosen because factor "time exposure" plays an important role in influencing SS and SP scores (Jerome et al., 2005), and therefore, exposing the same participants to both scenarios could have affected their level of SS and SP in the second scenario. In addition, to reduce the variability issues, a large sample of 125 participants were recruited. However, as an additional limitation of the study, the sample was skewed more towards the younger age group, with only 8.1% of the total sample older than 45 years. Nevertheless, it is important to mention that the actual population in Qatar with more than 45 years old is around 11.5%, with only 2.4% that are 60 years old or elder (Planning and Statistics Authority 2019). Considering the importance of the factor "age" in SS, the results may vary for a sample with a higher ratio of elderly drivers. The findings of this study could be a base for future studies on different sample composition (such as elderly driving population) to validate the transferability of the results.

Finally, in order to establish a baseline for the SS symptoms, the SSQ is recommended to be administered also before the experiment (Kennedy et al., 1993). Therefore, the results of this study concerning the relationship between demographic characteristics SS scores might be biased due to the physiological state of participants before the exposure. However, according to Young, Adelstein, and Ellis (2007), exposing participants to pre-SSQ could also bias their answers during post-exposure due to learning effects, i.e., participants may perceive that the appropriate answer would be to report differences between pre- and post- exposures.

6. Conclusion

This study investigated the impact of demographic factors on SS and the correlations between SS and SP subscales. Moreover, the impact of the road environment on these subscales was studied. The results showed that females are more vulnerable to SS than males and that the severity of symptoms increases with age. Moreover, an urban road environment with buildings close to the roadway and lower speed limits could increase SP and decrease the severity of SS. The resolution and quality of simulation scenarios could also contribute to increasing SP that alternatively could reduce the severity of SS symptoms. Furthermore, additional training (including oculomotor exercises) in a medium-fidelity driving simulator is recommended if drivers are requested to drive in higher speed scenarios.

In conclusion, the results of this driving simulator study provide insights into the influencing factors for each subscale of SP on the subscales of SS. Researchers should take the characteristics of the study sample into account and make additional adjustments in the simulator and scenario setting to counteract SS symptoms.

CRediT authorship contribution statement

Mustafa Almallah: Conceptualization, Writing - original draft, Data curation. **Qinaat Hussain:** Conceptualization, Investigation, Methodology, Formal analysis, Writing - review & editing. **Nora Reinolsmann:** Methodology, Writing - review & editing. **Wael Alhajyaseen:** Project administration, Supervision, Funding acquisition, Validation, Methodology, Writing - review & editing.

Acknowledgement

This publication was made possible by the NPRP award [NPRP11S-1228-170143] from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the author[s]. Open Access funding provided by the Qatar National Library.

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