

Factors Associated with Simulator Sickness in a High-Fidelity Simulator

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Sickness related to simulator use is a common problem that researchers face when designing experiments. The amount of time in the simulator, the number and length of drives, and the type of maneuver can be limited to minimize the likelihood of simulator sickness occurrence. This research describes the impact of time in a full motion simulator and number of drives on simulator sickness. Data from 11 studies representing 12 unique data sets using the National Advanced Driving Simulator will be examined. To access simulator sickness, a modified version of the Simulator Sickness Questionnaire (SSQ) was administered to participants in varying numbers and at various times depending on type of study and length of time. Regardless of the number of times the SSQ was collected, this paper examines the scores after the participant's last drive for a day in the simulator and the attrition rates. The results show that the sickness-related attrition rates across the data sets is low, at 2.45% compared to reported attrition rates with other simulators. Over half of the participants who withdrew came from two similar studies that required a secondary task of using a cellular phone. This paper will address simulator sickness and categorize contributing factors associated with the maneuver type and length of exposure to the simulator.

Introduction

Simulator sickness is a phenomenon similar to motion sickness that is experienced by many simulator users. Simulator sickness can range from mild to severe and typically manifests itself in a variety of symptoms, including general discomfort, eye strain, dizziness, nausea, and, in the most severe cases, vomiting. Besides the inconvenience to simulator users, the greatest concerns regarding simulator sickness are that it compromises the validity of training and data derived in the simulator device, lowers user acceptance, and in the most extreme cases, results in negative transfer-of-training.

There is a need for greater understanding of the phenomenon in order to maximize simulator effectiveness. While the incidences of simulator sickness and the threats to validity are frequently mentioned in the literature, there are few empirical studies of the phenomenon in general simulation or in driving simulation specifically.

This paper analyzes simulator sickness severity trends over a series of simulator studies conducted in a high-fidelity driving simulator. It attempts to determine variables that contribute to simulator sickness and is offered in lieu of a series of controlled studies specifically designed to validate or refute simulator sickness theory.

Factors Associated with Simulator Sickness

While experts do not entirely agree on the causes of simulator sickness, most attribute it to three factors: simulator design, type of simulator exposure, and individual susceptibility. These categories are not mutually exclusive, and the fact that they are intertwined complicates the study of simulator sickness. For the purposes of this paper, we will not discuss the role individual susceptibility plays as a factor contributing to simulator sickness.

Simulator Design

Simulator design plays a significant role in reducing or eliminating the sickness problem (Casali and Wierwille, 1980) because simulators produce a mismatch between sensory cues. This mismatch has been explained by perceptual conflict theory; that is, information provided by visual, vestibular, and proprioceptive cues in the simulator disagrees with inputs expected by the driver (Reason and Brand, 1975). This results in a number of false cues—and simulator sickness for the driver. Cue conflict can be the result of a mismatch between simulator subsystems (e.g., motion and visuals) or of a disparity in a single subsystem (e.g., cue filtering of the motion system) (Kennedy, Hettinger, and Lilienthal, 1990). This area has been widely studied, but few results are applicable to all simulators because of differences in fidelity, subsystem features, and configurations.

Simulator Exposure

Simulator sickness is also related to the duration and type of simulator exposure. The incidence of simulator sickness rises with the number of 90-degree turns and the need for braking (Romano and Watson, 1994). Research in flight simulation and other virtual environments has shown that sickness also increases with the length of exposure (Fowlkes, Kennedy, and Lilienthal, 1987), optical flow in the peripheral visual field (McCauley and Sharkey, 1992), luminance (Pausch, Crea, and Conway, 1992), and acceleration rates (McCauley and Sharkey, 1992).

Focus of This Paper

This paper looks at the relationship between several simulator exposure variables and simulator sickness severity in a high-fidelity driving simulator across a series of studies. By controlling for the factors associated with a single simulator device, the exposure trends provide a unique glimpse into how exposure time and the frequency and severity of driving maneuvers contribute to reported sickness scores and attrition.

Limitations

The data analyzed in this paper were derived from human factors safety studies. The inclusion and exclusion criteria for these studies screened out individuals with high levels of motion sickness susceptibility. The findings of this paper should only be generalized to drivers with little or no reported motion sickness history in real-world transportation modes.

Study findings are best generalized to high-fidelity driving simulation where motion cues mimic those in the real-world setting. The trends for lower-fidelity devices or simulators for other transportation modes are likely to differ.

Methodology

Apparatus

All studies surveyed in this paper used the NADS-1, a high-fidelity simulator located at the National Advanced Driving Simulator (NADS) facility at The University of Iowa. NADS-1 consists of an entire car, sport utility vehicle, or truck cab mounted inside a 24-foot dome. Four hydraulic actuators attached to the cab produce vibrations emulating road feel. The whole dome is mounted on a yaw ring that can rotate the dome about its vertical axis by 330 degrees in each direction. The X-Y assembly produces lateral and longitudinal accelerations by moving about a 64-foot by 64-foot bay. The NADS-1 motion system is capable of providing the driver with realistic motion cues that allow the driver to feel acceleration, braking, and steering, as well as experience extreme maneuvers generally associated with critical driving events.

The visual system consists of eight Liquid Crystal Display (LCD) projectors that project visual imagery on the inside of the dome. The imagery wraps 360 degrees around the driver. Higher resolution is utilized in the forward field-of-view to accommodate better feature recognition and reduce eye fatigue.

Studies

The studies selected for this paper met the following criteria: they used an automobile or sport utility vehicle cab, had a full field-of-view, did not involve a screening drive, and did not involve the testing of a pharmaceutical drug. Eleven different studies were selected. One study was divided into 2 data sets because participants completed study drives on different days. Table 1 describes the purpose, number and duration of drives, the driving environment, and maneuvers for the selected studies.

Table 1 Study Descriptions

Study	Description
1	Purpose: Investigate the response of non-expert drivers, and resulting vehicle motions, to simulated tire failures under various scenarios. 3 drives: 1 practice drive (4 min), 2 main (6 min per drive). Environment: 4-lane highway with 2 lanes traveling in each direction. 55 to 75 mph speed limit. Maneuvers: 4 non-severe brakes, 4 non-severe lane changes, 6 shallow curves.
2a	Purpose: Prepare for a study investigating braking and steering maneuvers. 34 main drives (3 min per drive). Environment: 4-lane highway with 2 lanes traveling in each direction. 30, 45, and 60 mph speed limit. Maneuvers: 17 non-severe brakes, 17 severe brakes.
2b	Purpose: Prepare for a study investigating braking and steering maneuvers. 22 main drives (3 min per drive). Environment: 4-lane highway with 2 lanes traveling in each direction. 30 and 60 mph speed limit. Maneuvers: 11 non-severe lane changes, 11 severe lane changes, 22 non-severe brakes.
3	Purpose: Compare driver performance in critical loss-of-control situations with and without activation of an Electronic Stability Control (ESC) system. 4 drives: 1 practice (4 min), 3 main (3 min per drive). Environment: 2-lane rural highway with dry pavement. 65 mph speed limit. Maneuvers: 1 severe curve, 1 shallow curve, 4 non-severe brakes, 2 severe lane changes, 8 normal lane changes.
4	Purpose: Evaluate the effects of cell phone use on driver performance in a highway environment. 8 drives: 4 practice (6 min per drive), 4 main (16 min per drive). Environment: 4-lane highway with 2 lanes traveling in each direction, 4 interchanges. 60 mph speed limit. Maneuvers: 1 severe brake, 19 non-severe brakes, 28 non-severe lane changes, 10 shallow curves.
5	Purpose: Evaluate driver performance associated with Adaptive Cruise Control (ACC) and Forward Collision Warning (FCW) systems. 2 drives: 1 practice (11 min), 1 main (35 min). Environment: 4-lane urban freeway with two lanes traveling in each direction. 65 mph speed limit. Maneuvers: 2 severe brakes, 19 non-severe brakes, 1 non-severe lane change.
6	Purpose: Evaluate the effects of cell phone use on driver performance in an urban environment. 7 drives: 4 practice (1-30 min, 3-5 min), 3 main (20 min per drive). Environment: 4-lane urban highway with 2 lanes traveling in each direction, traffic lights, and other scenario vehicles. 45 mph speed limit. Maneuvers: 46 non-severe brakes, 31 non-severe lane changes, 22 shallow curves.
7	Purpose: Evaluate the effectiveness of ESC in critical loss-of-control situations when driving on wet pavement. 7 drives: 2 practice (10 min total), 5 main (3 min per drive). Environment: 2-lane rural highway with wet pavement. 65 mph speed limit. Maneuvers: 1 severe curve, 5 severe lane changes, 7 non-severe brakes, 14 non-severe lane changes, 1 shallow curve.
8	Purpose: Evaluate the effect of various lane change collision avoidance systems on driver performance. 6 drives: 1 practice (15 min), 5 main (32 min per drive). 1 5-minute break scheduled after drive 2. Environment: 4-lane commercial and industrial roadways without a center turn lane. 50 mph speed limit. Maneuvers: 21 shallow curves, 16 non-severe brakes, 54 non-severe lane changes.

Study	Description
9	Purpose: Evaluate the effect of various lane change collision avoidance systems on driver performance. 6 drives: 1 practice (15 min), 5 main (32 min per drive). 3 breaks: 1 10-minute break to complete field-of-view test after drive 2, 2 15-minute breaks after drive 2 and drive 4. Environment: 4-lane commercial and industrial roadways without a center turn lane. 50 mph speed limit. Maneuvers: 22 shallow curves, 17 non-severe brakes, 54 non-severe lane changes.
10	Purpose: Evaluate the effectiveness of ESC in critical loss-of-control situations when driving on dry pavement. 7 drives: 2 practice (10 min total), 5 main (3 min per drive). Environment: 2-lane rural highway with wet pavement. 65 mph speed limit. Maneuvers: 1 severe curve, 5 severe lane changes, 7 non-severe brakes, 14 non-severe lane changes, 1 shallow curve.
11	Purpose: Evaluate novice drivers' performance in the simulator under various driving conditions. 5 drives: 3 practice (18, 30, 5 min, respectively), 2 main (30 min, 20 min, respectively). Environment: Main drive 1 consisted of a 4-lane interstate highway with 2 lanes traveling in each direction, 2-lane rural roadway, 2-lane urban roadway. Speed limit ranged from 25 to 70 mph. Main drive 2 consisted of a 4-lane urban highway with 2 lanes traveling in each direction, traffic lights, and other scenario vehicles. Maneuvers: 39 non-severe brakes, 25 non-severe lane changes, 1 severe curve, 26 shallow curves, 16 ninety-degree turns.

Independent Factors

Several variables were analyzed to determine how the duration and type of exposure affect participant attrition and sickness severity. Although analyzed separately, the variables were grouped into time and maneuvers for the purpose of description and interpretation.

Time. The length of exposure and breaks between exposures were divided into the following variables for analysis: number of drives, length of main study drive(s), number of scheduled breaks between study drives, scheduled time in the simulator, mean time in the simulator, minimum simulator time, and maximum simulator time.

Maneuvers. The type and frequency of driving maneuvers were categorized into the following variables: number of severe braking maneuvers, number of non-severe braking maneuvers, number of severe lane changes, number of non-severe lane changes, number of severe curves, number of shallow curves, and number of 90-degree turns.

Dependent Measures

Two dependent measures of simulator sickness severity were analyzed. The first dependent measure was the number of participants who withdrew after enrollment and therefore did not complete their study participation. The second dependent measure was the severity of simulator sickness, which was measured by a survey administered to participants immediately after simulator exposure.

Attrition. Attrition was the number of participants who chose to discontinue participation in the study due to simulator sickness. It is reported as a frequency for the purpose of this analysis.

Simulator Sickness Severity. The Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum, and Lilienthal, 1993) was used to measure sickness severity immediately after completion of all study drives. Participants rated the severity of 16 symptoms on a four-point Likert Scale (none, slight, moderate, and severe) to provide a continuous total score and three sub-scale scores of simulator sickness severity. The sub-scales are nausea (nausea, stomach awareness, salivation, burping, etc.), oculomotor (eye strain, difficulty focusing, blurred vision, etc.), and disorientation (dizziness, vertigo, fullness of head, etc.). The score ranges for each of the scales are: 0 to 235.6 for the total sickness score (SSQ); 0 to 200.3 for nausea subscale (NScore), 0 to 159.2 for the oculomotor (OScore), and 0 to 292.3 for disorientation subscale (DScore). In each case, zero represents the absence of simulator sickness symptoms and the maximum score indicates the most severe rating on that scale.

Analysis Method

Study documentation for each study was examined to determine type of maneuvers, number of drives, and exposure time. Several simulator sickness questionnaires may have been collected during a participant's study drives; this paper examines only those scores collected after the participant's last simulator drive. The mean scores for SSQ, NScore, OScore, and DScore were then determined for each study. Pearson product moment correlations were calculated, but no interactive effects were analyzed.

Results

Results can be summarized into areas of attrition, maneuver type, and time of exposure. The results across studies showed a range of Total mean SSQ scores from 9.93 to 34.89, N mean scores from 7.30 to 82.28, O mean scores from 7.20 to 26.90, and D mean scores from 8.58 to 35.14. Table 2 represents the Pearson product moment correlations for exposure variables and mean sickness scores.

Table 2 Person Product Moment Correlations for Exposure Variables and Mean Sickness Scores.

	Variable	Mean SSQ	Mean NScore	Mean OScore	Mean DScore	
	Attrition - Sickness	.81 _a	.79 _b	.51 _d	.77 _b	
TIME	Number of Drives	-.09	.05	-.17	-.20	
	Length of Main Study Drive	0.45 _e	0.17	0.75 _b	0.31	
	Number of Breaks During Study	-0.09	-0.22	0.19	-0.15	
	Scheduled Time of Simulator Use	0.37	0.14	0.63 _c	0.15	
	Mean Time in Simulator	0.27	0.04	0.56 _d	0.09	
	Minimum Time in Simulator	0.18	-0.06	0.58 _d	0.01	
	Maximum Time in Simulator	0.35	0.12	0.61 _c	0.11	
MANEUVER	Number of Severe Braking Maneuvers	0.00	0.03	-0.03	-0.08	
	Number of Non-Severe Braking Maneuvers	0.77 _b	0.87 _a	0.71 _b	0.82 _a	
	Number of Severe Lane Changes	-0.43 _e	-0.25	-0.54 _d	-0.43 _e	
	Number of Non-Severe Lane Changes	0.33	0.12	0.58 _d	0.12	
	Number of Severe Curves	-0.40 _e	-0.15	-0.40 _e	-0.18	
	Number of Shallow Curves	0.51 _d	0.47 _e	0.66 _c	0.49 _e	
	Number of 90° Turns	0.01	0.30	0.14	0.25	
	Legend	a = .80+	b = .70-.79	c = .60-.69	d = .50-.59	e = .40-.49

Attrition

Attrition ranged from 0% to 19% across the 12 data sets. Half the data sets showed attrition rates under 1%. A strong correlation was found between Total SSQ and attrition ($r^2 = .66$) as well as NScore and attrition ($r^2 = .63$). A moderate correlation was found with DScore and attrition ($r^2 = .59$). Attrition and OScore did not show a significant relationship.

Exposure Time

The length of a study drive ranged from 3 minutes per main study drive to 35 minutes per study drive. A moderate relationship was found between length of drive and OScore ($r^2 = .56$). No significant relationships were found with any of the other subscales.

The average length of time in the simulator ranged from 23 minutes to 4 hours and 32 minutes. Total SSQ, NScore, and DScore did not show any significance with average time in the simulator. OScore showed only a slight relationship ($r^2 = .32$). O score also showed a slight relationship with minimum time in simulator ($r^2 = .33$) and maximum time in simulator ($r^2 = .38$).

Maneuver

Braking

Non-severe braking maneuvers and simulator sickness scores showed the strongest correlation. Correlations were found corresponding to the number of non-severe braking maneuvers with all four subscales of simulator sickness. The number of non-severe braking events completed by the participants ranged from 4 to 46. Strong correlations were found with NScore ($r^2 = .76$), OScore ($r^2 = .66$), and Total SSQ ($r^2 = .60$). A moderate relationship was found with DScore ($r^2 = .50$)

Shallow Curves

The number of shallow curves in scenario drives showed a moderate correlation to mean OScore ($r^2 = .44$). The number of shallow curves present across the studies ranged from 0 to 22. The subscales for Total SSQ, NScore, and DScore did not show a significant relationship.

Lane Changes

The number of non-severe lane changes in the studies ranged from 0 to 54. A slight correlation was found with the OScore ($r^2 = .33$). Total SSQ, NScore, and DScore did not show any significance.

Discussion

This analysis set out to gain a better understanding of the effects of exposure and maneuver type on simulator sickness and attrition in a high-fidelity motion simulator. Not surprisingly, nausea scores were highly related to attrition; increases in reported nausea-related symptoms corresponded with greater attrition rates. Although nausea scores and disorientation scores greatly affected attrition, oculomotor scores did so to a lesser degree, indicating that people can tolerate higher levels of oculomotor discomfort and continue driving.

Time did not have the impact on simulator sickness scores that was expected. It was anticipated that as time in the simulator increased, the sickness scores would increase correspondingly. The only measure of simulator sickness that was affected by overall time in the simulator was the oculomotor score, and this relationship was small. The length of drive had a moderate effect on oculomotor scores, demonstrating a preference for shorter individual drives where possible to minimize ocular strain. The utilization of shorter drives allows for more time to be spent in the simulator per participant without experiencing these high levels of oculomotor strain.

Maneuvers had a much greater impact on simulator sickness than did time in the simulator. Surprisingly, the maneuver having the most impact on sickness was mild braking events. Every subscale of simulator sickness had a relationship with the non-severe braking maneuvers. It had been anticipated that severe maneuvers, particularly braking maneuvers, would have greatest impact on sickness due to the extreme nature of these events and the associated motion cueing; however, this was not borne out by the data. The reason for this is unclear; however, it could be that the short duration of severe events mitigates any cue mismatches that are present, while in short braking events any

cue mismatches become more pronounced with repetition throughout the drive. This would seem to indicate that decreasing the number of braking maneuvers experienced by participants would aid in lowering overall simulator sickness.

Conclusions

The mean simulator sickness scores found in these studies are generally quite low compared to reported scores from lower-fidelity simulators. Although these scores are quite low, the results show that they can be decreased. There is little from this analysis that would support the current trend of reducing the duration of individual simulator drives or limiting the length of total exposure in order to reduce the occurrence of simulator sickness. Also, contrary to general expectations, severe maneuvers are not the driving force in high SSQ scores or attrition. Instead, more mundane maneuvers such as periodic low-level braking maneuvers are more problematic. This warrants further investigation into why these mundane maneuvers seem to have a greater impact on sickness scores than anticipated and whether there is a threshold for the number of these types of maneuvers that could be included in a study without risk of increasing sickness and its related attrition.

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