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Predictors of Simulator Sickness Provocation in a Driving Simulator Operating in Autonomous Mode

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Abstract: Highly autonomous vehicles (HAV) have the potential of improving road safety and providing alternative transportation options. Given the novelty of HAVs, high-fidelity driving simulators operating in an autonomous mode are a great way to expose transportation users to HAV prior to HAV adoption. In order to avoid the undesirable effects of simulator sickness, it is important to examine whether factors such as age, sex, visual processing speed, and exposure to acclimation scenario predict simulator sickness in driving simulator experiments designed to replicate the HAV experience. This study identified predictors of simulator sickness provocation across the lifespan (N = 210). Multiple stepwise backward regressions identified that slower visual processing speed predicts the Nausea and Dizziness domain with age not predicting any domains. Neither sex, nor exposure to an acclimation scenario predicted any of the four domains of simulator sickness provocation, namely Queasiness, Nausea, Dizziness, and Sweatiness. No attrition occurred in the study due to simulator sickness and thus the study suggests that high-fidelity driving simulator may be a viable way to introduce drivers across the lifespan to HAV, a strategy that may enhance future HAV acceptance and adoption.

Keywords: simulator sickness provocation; autonomous vehicle technology; high-fidelity driving simulator

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1. Introduction

Highly autonomous vehicles (HAVs; Levels 4–5; Society of Automotive Engineers International) [1] may improve safety on the road, reduce traffic congestion, decrease energy consumption, and provide individuals with enhanced transportation options [2]. However, these potential benefits will only occur if HAVs are accepted and adopted by the general public. Barriers to adoption include users' concerns about the safety, affordability, availability, accessibility, usability, and reliability [3,4]. Driving simulators are a viable method to safely introduce HAVs to potential users, in a controlled environment [5,6]. A primary concern for using driving simulators is simulator sickness, which includes symptoms such as sweating, vomiting, nausea, and dizziness [4,7]. If simulator sickness can be mitigated, this mode of exposure to HAVs may be used to increase drivers' acceptance practices [8].

Understanding the predictors of simulator sickness may yield important knowledge to inform simulator sickness mitigation strategies. Earlier studies report that older females (i.e., >64 years old) are most susceptible to simulator sickness compared to both younger drivers and age-matched male drivers [9–12]. However, simulator sickness provocation in a driving simulator operating in autonomous mode has not been studied extensively, and may differ by age and sex. Likewise, studies indicate that associations exist between visual spatial functions, and age-related cognitive changes in simulator sickness provocation [13,14]. Studies showed the effectiveness of reducing simulator sickness symptoms via exposure

to an acclimation scenario [15,16]. Therefore, this study quantified simulator sickness provocation after exposing drivers (N = 210) throughout the lifespan (18–91 years old) to a driving simulator operating in autonomous mode; and elucidated the relationships between simulator sickness provocation and drivers' age, sex, visual processing speed, and exposure to an acclimation scenario as predictors of simulator sickness provocation.

1.1. Driving in a High-Fidelity Simulator

Driving simulators are used in research to safely expose drivers to in-vehicle technology [17]. High-fidelity driving simulators provide an immersive environment with enhanced visual and auditory cues. These simulators operate on principals of behavioral fidelity to enhance realism of the experience [18].

Studies on driving simulators operating in autonomous mode are only starting to emerge [4,6,19]. Early findings suggest that older drivers' perceptions of HAVs improved after being exposed to the driving simulator in autonomous mode (Level 4, SAE) [8]. Thus, high-fidelity driving simulators may be a viable mode of exposure to examine drivers' acceptance of HAV technology. However, some concerns exist regarding simulator sickness and attrition that may occur while driving in high-fidelity simulators [4,20,21].

1.2. Simulator Sickness

Drivers are more likely to experience simulator sickness with longer exposure to simulation, navigating scenarios involving turns and infrequent stops, and driving at high speeds [10,21]. Balk and colleagues [21] used a driving simulator in manual mode and 72 out of 530 participants reported simulator sickness symptoms, with a 14% dropout rate. Another study that tested 121 participants in a high-fidelity driving simulator in manual mode had a 29.75% dropout rate due to simulator sickness [22]. Few studies have explored simulator sickness provocation in a driving simulator in autonomous mode. For the studies that did investigate this phenomenon, mixed results exist. For example, some researchers report onset of simulator sickness symptoms, but no attrition; and others indicate 20% attrition of participants due to simulator sickness [5,6,23]. Therefore, a better understanding of simulator sickness provocation in a high-fidelity driving simulator running in autonomous mode is necessary.

1.3. Age and Sex

Matas and colleagues [11] tested 88 older drivers (>64 years old) in a low-fidelity driving simulator and 52 participants dropped out from the study due to simulator sickness. Likewise, Kawano et al. [14] found that simulator sickness was more likely to occur in older adults (60–79 years old) compared to younger adults (29–43 years old). Similarly, when younger adults (18–39 years old) and older adults (>64 years old) were exposed to a driving simulator, older adults experienced more simulator sickness when compared to younger adults [22]. All of these studies used a driving simulator in manual mode. One study did explore the effects of simulator sickness in a driving simulator in autonomous mode (Level 4, SAE) among 104 older drivers (65–91 years old) and found no age effects for simulator sickness provocation between young-old (65–74 years old) and old-old ($\geq$75 years old) drivers [5]. Comparing older drivers to a younger cohort though, may elucidate age-related factors that influence the likelihood of experiencing simulator sickness.

Sex is a predictor of simulator sickness as older female adults (vs. older males) are more susceptible to simulator sickness provocation in a driving simulator [7]. Possible explanations include well documented age-related declines in the vestibular-ocular system as well as increased age-related dizziness [7,24,25]. The mechanisms for sex-related differences in simulator sickness occurrence are not well understood, but postulations include hormone differences, response bias, and duration of exposure [22]. We are unsure if simulator sickness provocation may differ by sex after exposure to a driving simulator running in autonomous mode; therefore, understanding the effects of age and sex on

simulator sickness provocation in a driving simulator in autonomous mode (Level 4, SAE) is necessary.

1.4. Visual Processing Speed and Acclimation Scenario

Sensitivity in the visual system is associated with simulator sickness [26], and visual spatial functions have been associated with simulator sickness provocation [13,14]. Likewise, Matas et.al. [11] found a weak trend of slower visual processing speed accounted for dropout due to simulator sickness. However, this study used a low-fidelity driving simulator in a manual mode.

Acclimation scenarios help the driver to adapt and experience less simulator sickness. For example, Domeyer et al. [15] reported participants with a two-day gap between initial acclimation to the driving simulator and driving simulation session experienced reduced simulator sickness symptoms. Schweig et al. [16] noted that adaptation to the simulator led to lower probability of experiencing simulator sickness. However, we are not yet certain if visual processing speed and/or exposure to acclimation scenarios will contribute (or not) to simulator sickness, when participants are exposed to a driving simulator running in autonomous mode.

1.5. Rationale and Significance

While older age and sex (i.e., women) are associated with simulator sickness provocation in a high-fidelity driving simulator running in manual mode, slower visual processing speed contributes to dropouts due to the onset of simulator sickness; and exposure to acclimation scenarios alleviates the onset of simulator sickness symptoms. However, whether these associations also occur during exposure to a highly autonomous driving simulator, is unknown.

1.6. Purpose

The purpose of this study is to identify if (a) age, (b) sex, (c) visual processing speed, and (d) exposure to an acclimation scenario, are predictors of simulator sickness in drivers across the lifespan, who have been exposed to a high-fidelity driving simulator operating in an autonomous mode (SAE Level 4). By having a better understanding of the predictors of simulator sickness acquired in the driving simulator operating in autonomous mode, and correspondingly managing the simulator sickness symptoms, we are better able to measure drivers' acceptance of HAVs based on their exposure to the simulator.

2. Materials and Methods

2.1. Ethics

The University of Florida's Institutional Review Board (IRB) reviewed and approved the study (IRB201801988, IRB202000464). Prior to enrolment in this study, all participants provided written informed consent. Each participant received a $25 VISA gift card for study participation.

2.2. Design

This study is a secondary analysis from the parent study, a crossover-repeated measures design, that exposed older, middle-aged, and younger drivers to an autonomous shuttle and a driving simulator operating in autonomous mode (SAE level 4) [8,27]. This secondary analysis utilizes age, sex, Trail Making Test Part A (TMT-A; [28]), and the data from the Motion Sickness Assessment Questionnaire (MSAQ; [7]) scores from drivers (18–91 years old), who were exposed to the driving simulator running in autonomous mode [8].

2.3. Recruitment

Study flyers were distributed via social media sites, public venues, and stakeholder groups to obtain referrals for recruitment in North-Central Florida. Phone calls and emails were used to communicate and screen participants.

Participants

Participants (N = 210; 18–91 years old) completed the study for the period 17 October 2018 to 31 July 2021. Eligible participants included those with a valid driver's license and who were driving in the past six months. Participants were excluded from the study if they were unable to communicate in English, could not commute to the testing locations, or displayed signs of moderate cognitive impairment (i.e., <18 on the Montreal Cognitive Assessment; MoCA [29]).

Because this study occurred during the pandemic, the research team diligently followed the Centers for Disease Control and Prevention (CDC) and University COVID-19 guidelines (see Procedure), to support the safety of both the research participants and personnel.

2.4. Setting

The research occurred in the Driving Simulator Lab, located in the Smart House at the Oak Hammock residential community, in Gainesville, Florida.

Equipment and Driving Simulator Scenario

The participants were exposed to a Realtime Technologies Inc. (RTI) (Figure 1) high-fidelity driving simulator, equipped with high-definition visual channels-forward channels creating 180-degree field of view, backward channels displaying rear view, liquid crystal display side mirrors and virtual dash display, and a full car cab with sound speakers and dynamic modules of driving inputs (i.e., accelerator, brake, steering). For a more detailed description of the driving simulator, see [27,30].

Figure 1. A high-fidelity driving simulator operating in an autonomous mode.

Participants were exposed to a simulated scenario, where the vehicle "drove" in an autonomous mode at 15 mph (Figure 2). The main simulator drive included a 10-min exposure to a scenario based on a route in downtown Gainesville with established face and content validity [27]. The scenario included one right turn, one left turn, two roundabouts, frequent stops, and navigating of the street network along with other road users such as pedestrians, vehicles, cyclists and motorcycles. The scenario represented daytime driving, in good weather conditions and non-peak traffic conditions. The video of the simulator scenario can be viewed from https://www.youtube.com/watch?v=kDObiycJUxA&feature=youtu.be (accessed on 29 October 2019) [27].

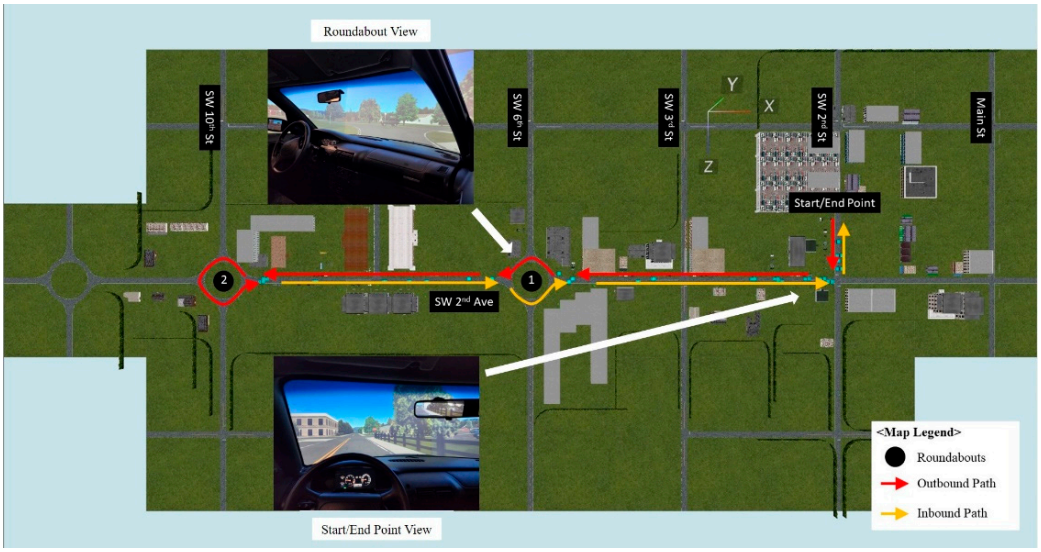


Figure 2. Route used in the driving simulator operating in autonomous mode.

2.5. Measurement

Independent variables: Age and sex were collected from a modified version of the demographic and health information form from the National Institute of Aging Clinical Research Toolbox [31]. Visual processing speed was assessed via the TMT-A [28]. TMT-A requires the participant to draw a line and connect the numbers from 1 to 25 consecutively. The total time (including administration, error point-out, and error-correction time) to complete the test is recorded in seconds, and the summary scores are compared with normative data to make a determination on whether set shifting is impaired. Greater test duration (i.e., more time) represents decreased cognitive performance. TMT A's test–retest reliability is between 0.76 and 0.89, and inter-rater reliability is 0.94 [32,33]. The standardized acclimation scenario [5,8] before the main drive was used as an independent variable to test the effects of the acclimation scenario on simulator sickness provocation.

Dependent variable: The MSAQ [7], was administered via an Apple iPad to assess the onset and severity of simulator sickness. The MSAQ is a four-item questionnaire that measures Queasiness, Nausea, Dizziness, and Sweatiness, with self-perceived symptom scores ranging from 0 (not at all) to 10 (severely). The MSAQ showed greater than 90% accuracy when categorizing individuals who could not complete the driving simulation because of simulator sickness provocation [7] and has great clinical utility as it can be administered and scored in less than one minute per participant.

2.6. Procedure

The team implemented the CDC and University directed COVID-19 protocols as follows: The researchers as well as the research participants had their temperature checked at the front door of the Smart House and wore face masks throughout the lab visit. Hand sanitizer was placed throughout the Smart House and the driving simulator was cleaned using antibacterial wipes before and after each participant visit. After the trained research assistant obtained written informed consent from the participants, participants completed baseline testing, which included obtaining their demographic information and completing the TMT-A assessment.

To reduce the simulator sickness provocation, each participant was informed of the simulator sickness protocol prior to their visit to the driving simulator lab [5,7,8,10]. The protocol included providing dietary recommendations for the night before the drive (e.g., avoid consuming alcohol, caffeine, or greasy food, and stay hydrated). The temperature in the lab was maintained at 72 degrees Fahrenheit during the simulation, with air circulation in the car cab of the simulator, via a fan. About half of the participants were assigned, via

random allocation, to complete a 5-min acclimation scenario to orient them to the driving simulator and operations in autonomous mode. The trained research assistant observed participants for the onset of simulator sickness symptoms [34]. Participants completed the MSAQ before and after exposure to the acclimation drive and the main drives in the driving simulator. Participants could terminate the drive if they experienced discomfort due to onset of simulator sickness symptoms.

2.7. Data Collection and Management

Trained research assistants collected and transferred the data into the University of Florida's Research Electronic Data Capture (REDCap) system [35], where it was stored. Each month, data integrity was inspected by a team member, and data input quality and completeness were inspected. No erroneous or missing data were found.

2.8. Data Analysis

Using mean (*M*) and standard deviation (*SD*), descriptive statistics quantified the corresponding age, sex, TMT-A scores, and exposure to an acclimation scenario. A Pearson correlation was conducted between age and TMT-A scores. Simulator sickness provocation was operationalized as an increase in MSAQ difference scores (post–pre), greater or equal to two, in each of the four MSAQ domains. A series of backward, stepwise multivariable binary logistic regressions was used to assess the association of age (continuous), sex (dichotomous), visual processing speed (i.e., TMT-A scores; continuous), and acclimation scenario (dichotomous) on participants' experience of simulator sickness provocation (dichotomous). A stepwise regression model known as "Stepwise Backward Regression" was used. It started with a complete (saturated) model that gradually removed variables at each step, to obtain a condensed model that best explained the data. The stepwise technique is beneficial since it reduces multicollinearity, identifies the significant predictors, and addresses overfitting of the data to the model [36]. The final model for each simulator sickness domain was determined using Akaike information criterion (AIC, [36]). Statistical significance was set to an alpha level of 0.05. The data analysis was performed using R version 4.1.3 (v4.1.3; [37]) in RStudio [37].

3. Results

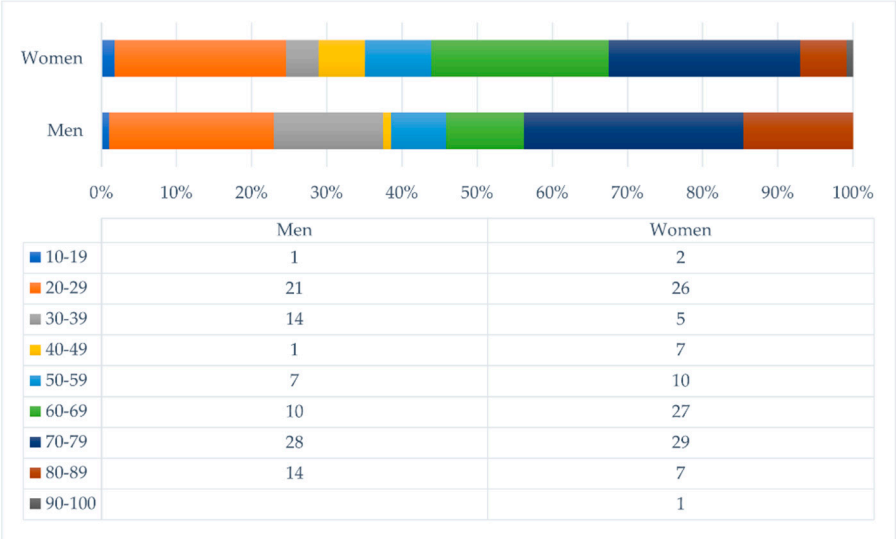
3.1. Demographics for Visual Processing Speed, Acclimation, and Simulator Sickness Provocation

Table 1 provides a description of the demographics of the participants.

A total of 210 participants (M_{age} = 55.08; *SD* = 22.24; 96 men; 114 women) ranging from 18 to 91 years old were exposed to the autonomous driving simulator scenario (See Figure 3). As expected, age was moderately correlated ($r = 0.52$, $p < 0.001$) with TMT-A scores. Based on randomization, 111 of 210 participants received the acclimation scenario prior to the autonomous drive. Roughly half (n = 107) of the participants reported MSAQ difference scores of zero. Pertaining to simulator sickness, participants reported no changes in Queasiness (n = 153; 73%), Nausea (n = 162; 77%), Dizziness (n = 131; 62%), and Sweatiness (n = 186; 89%). Those with "slight" simulator sickness symptoms reported a range from 0 to 8 (Queasiness *M* = 0.367; *SD* = 1.303, Nausea *M* = 0.814; *SD* = 1.687, Dizziness *M* = 1.081; *SD* = 1.82, Sweatiness *M* = 0.619; *SD* = 1.508, with the total MSAQ score ranging from 0 to 10). No participants dropped out of the study due to simulator sickness provocation.

Table 1. Demographic data.

Factor	Value	Frequency (%)
Sex	Male	96 (46%)
	Female	114 (54%)
Ethnicity	African American or Black	20 (10%)
	Asian/Pacific Islander	39 (18%)
	Caucasian or White	129 (61%)
	Hispanic or Latino	14 (7%)
	Multiracial	2 (1%)
	Would rather not say	1 (1%)
	Other	5 (2%)
Education	No high school diploma	1 (1%)
	High school graduate or equivalent	9 (4%)
	Some college credits	30 (14%)
	Trade/Technical/Vocational training	3 (2%)
	Associate degree	21 (10%)
	Bachelor's degree	53 (25%)
	Master's degree	61 (29%)
	Doctorate/Professional degree	32(15%)
Marital Status	Single, never married	69 (33%)
	Married or domestic partnership	108 (51%)
	Widowed	12 (6%)
	Divorced	21 (10%)
Employment	Part-time	25 (12%)
	Full-time	34 (16%)
	Retired	92 (44%)
	Unable to work	4 (2%)
	Student	48 (23%)
	Homemaker	5 (2%)
	Unemployed	2 (1%)



	Men	Women
10-19	1	2
20-29	21	26
30-39	14	5
40-49	1	7
50-59	7	10
60-69	10	27
70-79	28	29
80-89	14	7
90-100		1

Figure 3. Distribution of age—range by sex—frequency counts bar graph.

3.2. Predictors of Simulator Sickness Provocation

A series of multivariable binary logistic regressions was conducted to predict simulator sickness provocation (yes/no) using age, sex, visual processing speed (TMT-A scores), and acclimation scenario (exposed vs. no exposure). The initial models with all independent variables, final models after stepwise backward removal, and final models after stepwise backward removal with age as categorical (older; age of 65 or older, and younger; age in between 18–39 + middle-aged; age in between 40–64 years old) are displayed in Table 2.

Table 2. Models predicting simulator sickness provocation using age, sex, visual processing speed, and an acclimation scenario.

	Initial Full Models				**Final Models after Backward Stepwise Removal**					**Final Models after Backward Stepwise Removal (With Age as a Categorical Variable)**				
Queasiness	*b*	*SE*	*p*	Exp(B)	Queasiness	*b*	*SE*	*p*	Exp(B)	Queasiness	*b*	*SE*	*p*	Exp(B)
Age	−0.019	0.001	0.053	0.982	Age	−0.018	0.01	0.054	0.982	Age (Y + M)	0.722	0.392	0.066	2.058
Sex	−0.073	0.352	0.835	0.929	Sex	-	-	-	-	Sex	-	-	-	-
TMT-A	0.032	0.021	0.128	1.032	TMT-A	0.031	0.021	0.13	1.032	TMT-A	0.025	0.02	0.197	1.026
Acc	0.009	0.35	0.978	1.01	Acc	-	-	-	-	Acc	-	-	-	-
Nausea	*b*	*SE*	*p*	Exp(B)	Nausea	*b*	*SE*	*p*	Exp(B)	Nausea	*b*	*SE*	*p*	Exp(B)
Age	0.004	0.011	0.727	1.004	Age	-	-	-	-	Age (Y + M)	−0.201	0.481	0.676	0.818
Sex	0.006	0.416	0.988	1.006	Sex	-	-	-	-	Sex	-	-	-	-
TMT-A	0.055	0.029	0.059	0.06	TMT-A	0.06	0.025	0.015	1.062	TMT-A	0.055	0.027	0.045	1.056
Acc	0.245	0.418	0.557	1.278	Acc	-	-	-	-	Acc	-	-	-	-
Dizziness	*b*	*SE*	*p*	Exp(B)	Dizziness	*b*	*SE*	*p*	Exp(B)	Dizziness	*b*	*SE*	*p*	Exp(B)
Age	0.016	0.008	0.06	1.016	Age	0.016	0.008	0.062	1.016	Age (Y + M)	−0.577	0.36	0.109	0.562
Sex	0.227	0.324	0.483	1.255	Sex	-	-	-	-	Sex	-	-	-	-
TMT-A	0.04	0.021	0.049	1.041	TMT-A	0.041	0.021	0.047	1.042	TMT-A	0.048	0.019	0.011	1.050
Acc	0.083	0.032	0.798	1.087	Acc	-	-	-	-	Acc	-	-	-	-
Sweatiness	*b*	*SE*	*p*	Exp(B)	Sweatiness	*b*	*SE*	*p*	Exp(B)	Sweatiness	*b*	*SE*	*p*	Exp(B)
Age	−0.018	0.014	0.198	0.982	Age	-	-	-	-	Age (Y + M)	-	-	-	-
Sex	0.394	0.53	0.45	0.457	Sex	-	-	-	-	Sex	-	-	-	-
TMT-A	0.054	0.036	0.129	1.056	TMT-A	-	-	-	-	TMT-A	-	-	-	-
Acc	−0.058	0.526	0.912	0.944	Acc	-	-	-	-	Acc	-	-	-	-

Note: The significance level = 0.05; Y + M = Younger and middle-aged compared with older group; TMT-A = Trail Making Test Part A; Acc = Acclimation Scenario; *b* = Unstandardized beta; *SE* = Standard error; *p* = Probability value; Exp(B) = Odds ratio.

Slower visual processing speed predicted provocation of Nausea ($b = 0.06$, $p < 0.05$, 95% CI: 1.016, 1.119) and Dizziness ($b = 0.041$, $p < 0.05$, 95% CI: 1.002, 1.087) in the final models. Age trended toward signs of simulator sickness provocation for Queasiness ($b = -0.019$, $p = 0.053$, 95% CI: 0.963, 1.00) and Dizziness ($b = 0.016$, $p = 0.06$, 95% CI: 0.999, 1.033) in the initial model. Therefore, we categorized the age into two groups (older; 65–91 vs. younger and middle-aged; 18–64). The final model showed statistical significance for slower visual processing speed predicting Dizziness ($b = 0.048$, $p < 0.05$, 95% CI: 1.013, 1.092) and Nausea ($b = 0.055$, $p < 0.05$, 95% CI: 1.006, 1.121). No significant associations were observed for sex, or the acclimation scenario, with Queasiness, Nausea, Dizziness, or Sweatiness.

4. Discussion

The primary purpose of this study was to explore if drivers across the lifespan experience simulator sickness when exposed to the high-fidelity driving simulator operating in autonomous mode. The study examined whether age, sex, visual processing speed, and exposure to an acclimation scenario, predict simulator sickness provocation.

4.1. Age, Sex, Visual Processing Speed, Acclimation, and Simulator Sickness Provocation

Our sample included adults ranging from 18–91 years old. The study had slightly more female participants, which is not surprising given that Alachua County and the State of Florida have a higher female vs. male population [38]. Consistent with the existing literature, our study demonstrated a relationship between older age and slower visual processing speed [39–41]. We detected only minor complaints of simulator sickness, which

may be attributed to two reasons: First, we instituted an evidence-based simulator sickness protocol [5] which might have attenuated the simulator sickness provocation. Second, drivers were exposed to a scenario replicating low speeds, benign traffic, and no rapid acceleration or deceleration, which, if present, may have provoked simulator sickness [42]. Therefore, we were not surprised that the dropout rate for this study was zero.

4.2. Simulator Sickness Provocation

Drivers with slower visual processing speed are more likely to experience Nausea and Dizziness after exposure to the driving simulator. Matas et al. [11] established a weak trend of slower visual processing speed as it relates simulator sickness dropout. Similarly, in our study, the increased TMT-A scores predicted Nausea and Dizziness that are domains of simulator sickness. Contrary to previous studies [14,22], in our study, age was not a predicter of simulator sickness domains; however, age showed a trend toward predicting Queasiness ($p = 0.054$) and Dizziness ($p = 0.062$). Although no statistical significance existed between older age and slower visual processing speed in this study; future studies may want to investigate the causal effects of age, slowed visual processing speed and Queasiness and Dizziness, to make age-related inferences.

Contrary to previous studies with simulators running in manual mode, our study found no sex effect [7,11], nor exposure to an acclimation scenario effect, in predicting simulator sickness [15]. Iskander et al. [4] explained that previous studies on postural instability may make women more susceptible to simulator sickness than men, however, the driving simulator used in this study was fix-based, thus sex may have not been predicted simulator sickness symptoms due to anthropometric sex differences. Studies reported reduced simulator sickness and fewer simulator sickness symptoms after repeated exposure to the simulator, but repeated exposure to the simulator via acclimation scenario in this study did not predict any of the domains of the simulator sickness [15,16]. In a study by Haghzare et al. [6], five participants out of forty-five withdrew from the study due to simulator sickness after the initial sessions (i.e., two five-minute scenarios) that was intended to decrease the chances of experiencing simulator sickness by adapting to the simulator conditions. As studies report mixed results, further investigation is needed to determine whether acclimation scenarios help reduce simulator sickness symptoms and if they are necessary under driving simulator operating in autonomous mode.

Clearly, as we are standing on the brink of using driving simulators in autonomous mode, further scientific inquiry is needed to quantify: (a) if simulator sickness is truly a phenomenon to hinder participation in autonomous driving simulator studies; (b) the interaction between age and visual processing speed, as predictors of simulator sickness symptoms in the domains of Dizziness and Nausea; and (c) the cut-point scores of the predictor variables (in (a) and (b) above) to support participation in studies on driving simulator operating in an autonomous mode.

4.3. Limitations and Strengths

As we conducted a secondary analysis from a parent study, this study was not designed or powered to evaluate the aim of simulator sickness provocation. Findings of this study are relevant only to equipment and scenarios utilized in this study: i.e., 180-degree field of view high-fidelity driving simulator, using a relatively benign on-road scenario (limited speed of 15 mph, no uphill or downhill, no congested traffic situation such as in peak traffic), and running in autonomous (SAE Level 4) mode—all of which could have affected simulator sickness provocation. Furthermore, our simulator had a fixed base without motion, which cannot fully reproduce the experience of driving or riding in a vehicle with high fidelity. As such, we recognize that this study is prone to bias. For example, Berkson's bias, a type of selection bias is evident in our study because we utilized a convenience sample with participants mainly recruited from North-Central Florida. The study is also susceptible to the Hawthorne effect, as drivers were observed by the research assistant during simulator exposure. As such, they may have behaved (e.g., under-reporting or

over-reporting of simulator sickness symptoms) differently, because they knew that they were being observed. Self-selection bias might have occurred in our study, especially given that we recruited participants during the pandemic, meaning that only those who were not too concerned about the effects of exposure in a pandemic, enrolled in this study. Spectrum bias could be apparent due to the benign simulator scenario and elimination of environmental triggers that could have provoked simulator sickness. Given the above, the findings of this study are only generalizable to similar participants, conditions, and equipment that are consistent to those reported in this study.

The main strength of this study is that all four domains of simulator sickness were tested in a large sample of 210 participants representing drivers from across the life span in a high-fidelity and immersive driving simulator operating in autonomous mode (SAE Level 4). No attrition occurred as a result of simulator sickness and all participants completed the study. Although this study was completed during the COVID-19 pandemic, no COVID case onset was reported from any participants in this study.

5. Conclusions

We aimed to understand the predictors of simulator sickness in young, middle-aged, and older adults using a high-fidelity driving simulator running in autonomous mode. While we observed no effects for sex and exposure to an acclimation scenario, slower visual processing speed predicted Nausea and Dizziness. Age showed a trend toward predicting Queasiness and Dizziness, but requires further investigation in studies designed to causally examine such relationships. Interestingly, no participants dropped out from this study due to simulator sickness, indicating that a high-fidelity driving simulator is a viable method to expose participants to autonomous in-vehicle technology. To conclude, predictors of simulator sickness provocation were identified and further studies pertaining to these identified predictors may support managing simulator sickness symptoms. However, we also encourage authors to design primary studies for determining the effect of simulator sickness provocations in HAVs—which we could not infer from the data in this secondary analysis.

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