Projection Displays Induce Less Simulator Sickness than Head-Mounted Displays in a Real Vehicle Driving Simulator

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ABSTRACT

Driving simulators are necessary for evaluating automotive technology for human users. While they can vary in terms of their fidelity, it is essential that users experience minimal simulator sickness and high presence in them. In this paper, we present two experiments that investigate how a virtual driving simulation system could be visually presented within a real vehicle, which moves on a test track but displays a virtual environment. Specifically, we contrasted display presentation of the simulation using either head-mounted displays (HMDs) or fixed displays in the vehicle itself. Overall, we find that fixed displays induced less simulator sickness than HMDs. Neither HMDs or fixed displays induced a stronger presence in our implementation, even when the field-of-view of the fixed display was extended. We discuss the implications of this, particular in the context of scenarios that could induce considerable motion sickness, such as testing non-driving activities in automated vehicles.

CCS CONCEPTS

• **Human-centered computing → HCI design and evaluation methods**.

KEYWORDS

driving simulation, HMD, motion sickness, projection, simulator sickness, virtual reality, visualization

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INTRODUCTION

Driving simulators are an essential for developing and evaluating innovations in automotive technology for human users, from vehicle handling systems to in-vehicle user interactions. Critically, a simulated driving environment provides a safe option for user testing and the realism (or perceptual fidelity) of the simulation can vary immensely, depending on the reasons for user testing. For instance, while vehicle motion need not be necessary for discerning user preferences for instrument layout [15], it could be essential for evaluating vehicle control or situational awareness [24]. Regardless of their purpose, driving simulators should avoid inducing simulator sickness and aim to deliver a sense of presence in their users [3]. Failing to do so could compromise or even confound the findings obtained during simulation.

The current paper investigates how visualization of a simulated driving environment could be implemented in a real vehicle that travels on a test track, but nonetheless displays a virtual environment to its user that is aligned to the test track. This system is referred to as a Vehicle-in-the-Loop (VIL) simulator because it provides realistic vehicle handling capabilities as well as present actual vehicle motion to the user. Compared to existing concepts [9, 20] participants in the VIL control the vehicle them self which reduces time delay of input and also increases realism. However, the VIL poses non-trivial challenges with regards to the visual display of the driving environment and vehicle control. In this work, we address whether it is preferable to use a head-mounted display (HMD) or fixed display, such a windshield projection, in such a moving-base simulator and evaluate this in terms of simulator sickness and presence.

On the one hand, a fixed display is likely to ameliorate user experiences of simulator sickness. This is because it precludes issues caused by head-tracking inaccuracies and time delays. On the other hand, HMDs could offer a more immersive experience (depending on the layout of the fixed display) and, hence, induce a greater sense of presence. In the current work, we first compare the use of a HMD and a windshield projection in the VIL (Experiment 1). This experiment is designed to solve major problems of HMDs (e.g. simulator sickness, restricted user of vehicle interior). In line with our hypothesis, participants reported less simulator sickness when experiencing the windshield projection, compared to using a HMD. There were no notable differences for presence. In a follow-up experiment, we extended the field-of-view of the fixed displays in the VIL by introducing a monitor that visualized the external environment from the window of the passenger seat (Experiment 2). The extension of the field-of-view was done to allow a more realistic driving environment and allow for more outside interaction especially in urban scenarios. While we replicated the results on simulator sickness, there continued to be no notable differences in subjective reports of presence.

COMPARING HMD AND PROJECTION VISUALIZATION

Using fixed displays (i.e., projector display) in the VIL offers several advantages as well as drawbacks to using an HMD. In most instances, using a projector display removes the restriction of user movement due to HMD cables as well as their considerable weight (i.e., 1050g) (Figure 1). Besides this, the technical implementation of a projector display is relatively straightforward compared to the implementation of a HMD that relies on head-tracking to derive an accurate user perspective in real-time. However, the most significant drawback of projector displays is that it precludes the use of binocular vision to convey three-dimensional realism. Rendering stereoscopic images is easy with an HMD but non-trivial for projector displays. Depending on their implementation, using a combination of fixed displays can significantly increase the field-of-view while the field-of-view of a HMD cannot be changed; a typical HMD field-of-view has a horizontal view of 40 degrees and a vertical field of view of 32 degrees.

Psychological variables, like simulator sickness [26] or presence [32], may influence the behavior in driving simulators [3, 5]. The foundation to achieve behavioral validity, which allows the transfer from driving simulation to real vehicles, is low simulator sickness and presence [3]. Simulator sickness symptoms may cause participants to adapt their behavior to reduce simulator sickness symptoms [5]. However, the primary goal of using driving simulators is to achieve valid results that replicate outside the simulation environment and are behavioral valid. Using a projector may help to reduce simulator sickness compared to HMD [25]. Presence, defined as the subjective experience of being in an environment [32], is influenced by the human-machine interface, the operator's task, and individual cognitive factors [7]. Factors of the human-machine interface range from a restricted field-of-view to the use of multi-modal information [7, 32]. In summary, presence is a significant indicator of the quality of a virtual environment [16]. Using a projector instead of an HMD allows the interaction with the car interior and may increase the field-of-view. Thus, presence may be positively influenced.

VEHICLE-IN-THE-LOOP

The vehicle-in-the-loop (VIL) is a real car that is operated on a mapped test track. The VIL provides kinaesthetic, vestibular, and in parts, auditory feedback of a real car with a simulated visual view [2]. The visualization display of the driver's view can be a head-mounted display [2] or monitors and a projection screen (Figure 5) [22]. In summary, drivers experience the real interaction with the car while seeing a virtual environment. This gives researchers the possibility to conduct highly controlled experiments with real vehicle dynamics and, thus, the evaluation of human interactions with automated vehicles.

The VIL solves two challenges, (1) the mapping of the car onto a test track and (2) the visualization of a simulated environment mapped onto the test track. The mapping of the vehicle is done by an inertial measurement unit (IMU) and based on a differential GNSS (dGNSS)-signal received by the GNSS- and HF-antennas (Figure 5). To obtain highly accurate position data, a dGNSS-station on a known coordinate is needed.

These components provide accurate mapping of the vehicle on a test track. The visualization is done by constructing virtual environments (currently implemented in VIRES [28]) that are also mapped to the test track. A consumer computer does the fusion of the vehicle position and simulation. The front view is evaluated in this study.

The current implementation is an HMD (nVisor ST50 (1280x1024)) and a head tracker (Pst Base HD) installed in an Audi A6 Avant. The horizontal field-of-view is 40°; the vertical field-of-view is 35°. The view angles are not fixed as the head it tracked. Thus the view is adjusted accordingly.

To address the problems of simulator sickness, low presence, and restricted use of vehicle interior, a projection solution was implemented, which replaces the HMD-display. For this purpose, an Optoma ZW 212 short throw projector (1280 x 800) is installed in a second Audi A6 Avant [22]. The projector is mounted directly under the vehicle's roof (Figure 3). As a screen, which is a 0.45 m x 1.20 m white plastic cover is used, which is installed between the steering wheel and the windshield. The horizontal view angle of the projector is

Figure 1: HMD-Display sed in the VIL

Figure 2: In-Vehicle Display - Windshield projection of the outside

40°; the vertical view angle is 35° with a pitch of 3° rotated to the front. Both front side windows are covered, to minimize exterior lighting in the interior of the vehicle. In the second experiment, a passenger window view is implemented using a monitor (LG 21:9 UltraWide 29UM65) (Figure 4).

The main contribution of this study is an innovative approach to solving major issues with HMD-techniques for VIL driving simulators. By projecting a driving image onto a panel mounted between the steering wheel and windshield and an additional side monitor on the passenger side, the HMD can be eliminated. This eliminates issues with the HMD weight and the lack of ability to interact with vehicle interior [10]. We conducted a set of experiments that allow for comparison between (1) HMD, (2) Front projection, and (3) front and passenger side window projection.

METHOD

Equipment

Different configurations of the VIL visualization were examined. The VIL and the detailed visualization is described in the previous section "Vehicle-in-the-Loop". After the first experiment, we optimized the visualization of the HMD-display condition for realism, by readjusting the default head position by 1.3m backward. In Experiment 2, the front view angle

Figure 3: Projector mounted between driver and passenger seat

Figure 4: Extended In-Vehicle Display - Windshield and passenger window view of the outside

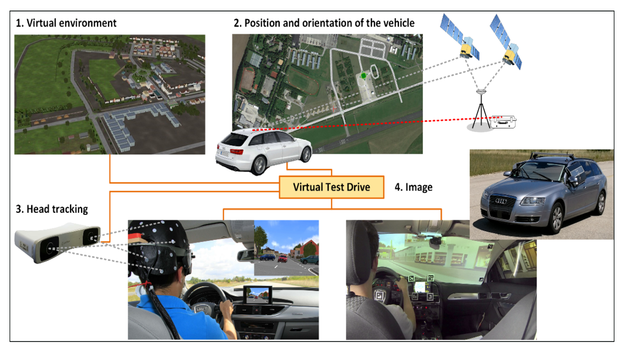

Figure 5: VIL concept [10]

of the in-vehicle display was set to an asymmetric angle of top 20°, bottom 15° and pitch 0°.

Table 1: Demographics of recruited participants

Experiment	N	Age	Gender	Duration
Experiment 1	30	29+/-11.6	15/15	50
Experiment 2	30	27+/-7.4	22/8	35

Participants

Altogether, 60 students and employees were recruited for this study. All participants were required to have driving experience of at least 10000 km per year. Participation in this study was voluntary and without compensation. The demographics of both experiments are presented in Table 1. All participants reported normal or corrected-to-normal vision and had no visible physical disabilities. Twelve participants in Experiment 1 had to be excluded due to technical issues.

Experimental Design and Measures

In both experiments, we chose a repeated measures within-subject design for the main independent variable of *Visualization* and evaluated its effect on the dependent variables of *presence* and *simulator sickness*. A within-subject design mitigated for high inter- and intra-participant variability of presence and simulator sickness measurements [25]. Each experiment consisted of two sessions for the blocked conditions of *Visualization* and always contrasted a HMD-display setup against an in-vehicle display that primarily featured a windshield projection display. The in-vehicle display system in Experiment 2 differed from Experiment 1, in that it had an additional monitor that represented the outside world view from the passenger window, hence extending the field-of-view. Test sessions were always separated by several days (i.e., 5-10 days) to minimize order effects [25]. Testing duration was designed to ensure that participants would experience some simulator discomfort, if at all, but optimized to avoid severe simulator sickness. Note that the test durations were shortened in Experiment 2 as a basis of participant feedback from Experiment 1 (Table 1); it has been previously demonstrated that 75% of the severe simulator sickness effects occur within the first 30min [26].

Presence was measured with the "presence in virtual environments" questionnaire [16]. The questionnaire includes twelve items regarding the quality of the interface. Each item ranges from 1 = very good, to 7 = very poor. The presence score is calculated as the arithmetic mean of all items. Simulator sickness was measured with the Simulator Sickness Questionnaire (SSQ) [14]. It consists of 16 items that load on three sub-scales: (1) nausea, (2) (visual-related) oculomotor disturbances, and (3) (vestibular-related) disorientation. Each item ranges from 0 (none) to 3 (severe). The scores of each sub-scale were calculated as well as a total score that was the weighted sum of the individual items [14]. Therefore the score of nausea range from 0 to 200.34, disorientation scores range from 0 to 292.32, and oculomotor disturbance scores range from 0 to 159.18 [8, 14].

Procedure

Familiarization phase. Participants were accustomized to the virtual environment prior to testing by driving freely along the test track. They were able to test the vehicle control dynamics, given the tested visualization of the session. Participants could experience the vehicle and virtual environment using slalom drives, acceleration, and deceleration maneuvers. The familiarization phase was the same in experiment 1 and experiment 2.

Testing phase. During testing, participants experienced naturalistic driving scenarios comparable to [21, 23]. The primary task was to simply follow a lead vehicle on a straight road, which travelled at a mean velocity of 50 km/hr, for 900 m and to maintain a headway distance between 15 to 35 m. Occasionally, the leading vehicle could indicate a right turn, before stopping at the side of the road. When this happened, participants were supposed to overtake the lead vehicle and drive through traffic delineator posts ahead of the lead vehicle that varied the available road width from 2.25 to 3.75 m. This signalled the end of a trial. Experiment 1 consisted of seven trials and Experiment 2, five trials. At the end of each session, participants completed a presence questionnaire [16] and simulator sickness questionnaires [14].

RESULTS

The current study compared visualization methods of the VIL driving simulator for simulator sickness and presence. In Experiment 1, we compared a HMD-display with a in-vehicle windshield projection display. In Experiment 2, we compare a HMD-display condition against an in-vehicle display that was extended with a passenger seat window visualization. In all conditions, we calculated simulator sickness in terms of nausea, oculomotor disturbance, and disorientation as well as an overall measure. The calculation followed the recommendation by [14]. Presence was calculated as the mean of all items on the related questionnaire. To reiterate, a high score for simulator sickness indicates more sickness while a high score for presence indicates less presence.

We performed a one-sided Bayesian paired-sample t-Test with a default Cauchy prior width of 0.707 within each experiment. We chose Bayesian analysis as they are more reliability, have better accuracy in noisy data, and are less proneness to type I error compared to frequentist analysis [30]. We report the Bayes Factor (BF) derived with JASP Team [11] and interpret our results in terms of the likelihood that the HMD-display generates a larger score than the in-vehicle display (H1), relative to the null hypothesis (H0). In other words, a BF_{+0}=3.0$ would suggest that the test hypothesis, namely that the HMD-display induced less presence (or more motion sickness) than the in-vehicle display, is three times more likely than a null hypothesis (for a tutorial, see [13] and [31]). We describe the evidence drawn from BF ranging

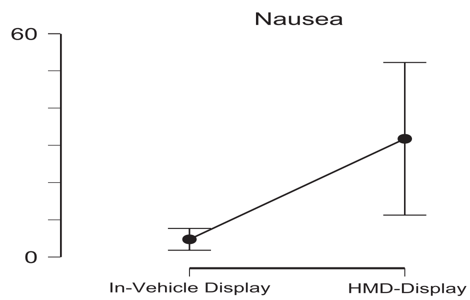

Figure 6: Nausea comparing means and 95% credible intervals of in-vehicle display with the HMD-display

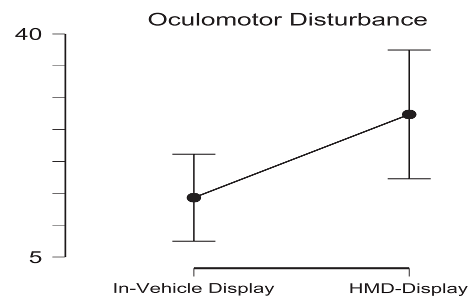

Figure 7: Oculomotor disturbance comparing means and 95% credible intervals of in-vehicle display with the HMD-display

from no evidence (BF = 1) to extreme evidence (BF > 100) [29].

Experiment 1: HMD-Display compared to In-Vehicle Display

Simulator sickness. The summary of the simulator sickness scores are illustrated in Figure 9 and, separately, the means of each sub-scale (1) nausea in Figure 6, (2) oculomotor disturbance in Figure 7, and (3) disorientation Figure 8. No participant dropped out because of simulator sickness. On the overall score for simulator sickness, there is "strong evidence" (BF0+ = 12.95; mean$_{In-VehicleDisplay}$ = 12.47, sd$_{In-VehicleDisplay}$ = 12.03; mean$_{HMD-Display}$ = 37.19, sd$_{HMD-Display}$ = 32.57) that a in-vehicle windshield display system reduces sickness compared to the HMD implementation. For the sub-scale of nausea, we found "substantial" evidence that using the in-vehicle windshield display decreased nausea compared to the HMD-display (BF_{+0}) was 6.77; mean$_{In-VehicleDisplay}$ = 4.77, sd$_{In-VehicleDisplay}$ = 5.9; mean$_{HMD-Display}$ = 31.8, sd$_{HMD-Display}$ = 41.26). In addition, there was "substantial" evidence that in-vehicle windshield display decreases oculomotor disturbance (BF_{+0} = 6.31; mean$_{In-VehicleDisplay}$ = 13.15, sd$_{In-VehicleDisplay}$ = 16.71, mean$_{HMD-Display}$ = 27.37; sd$_{HMD}$ = 20.33) and disorientation (BF_{+0} = 7.87; mean$_{In-VehicleDisplay}$ = 14.32, sd$_{In-VehicleDisplay}$ = 13.73, mean$_{HMD-Display}$ = 41.76, sd$_{HMD-Display}$ = 44.53).

Presence. The responses on the presence questionnaire are illustrated in Figure 10, which shows the mean presence for in-vehicle windshield display (mean$_{In-VehicleDisplay}$ = 2.10, sd$_{In-VehicleDisplay}$ = 0.88) and HMD-display (mean$_{HMD-Display}$ = 2.45, sd$_{HMD-Display}$ = 0.63). The analysis reveals "anecdotal evidence" for increased presence when an in-vehicle windshield display is used, compared to an HMD-display (BF_{+0} = 2.84).

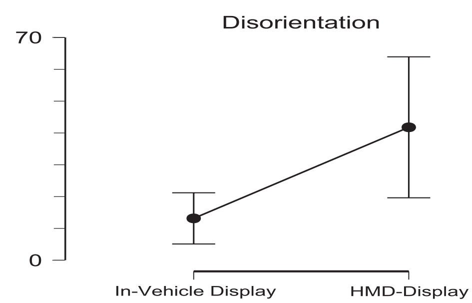

Figure 8: Disorientation comparing means and 95% credible intervals of in-vehicle display with the HMD-display

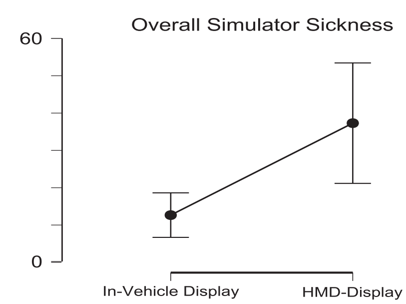

Figure 9: Overall simulator sickness comparing means and 95% credible intervals of in-vehicle display with the HMD-display

Experiment 2: HMD-Display compared to Extended In-Vehicle Display

Simulator sickness. The overall simulator sickness score is illustrated in Figure 14 and, separately, the means of each sub-scale (1) nausea in Figure 11, (2) oculomotor disturbance in Figure 13, and (3) disorientation Figure 12. No participant dropped out because of simulator sickness.

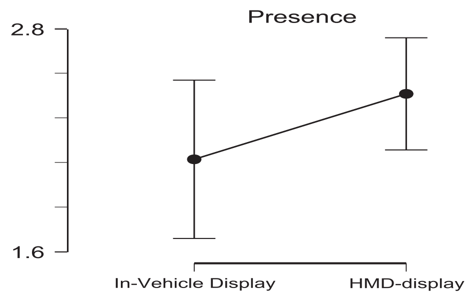

Figure 10: Presence comparing means and 95% credible intervals of in-vehicle display with the HMD-display

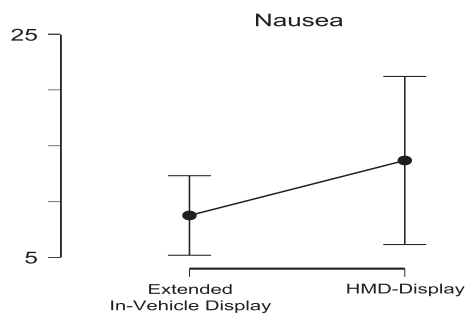

Figure 11: Nausea comparing means and 95% credible intervals of in-vehicle display extension with the HMD-display

There is "anecdotal evidence" that the in-vehicle display extension reduces overall simulator sickness compared to the HMD-display (BF_{+0}= 0.56; $mean_{In-VehicleDisplayExtended}$ = 19.42, $sd_{In-VehicleDisplayExtended}$ = 22.22; $mean_{HMD}$ = 19.42, sd_{HMD} = 15.75). Furthermore, we found "anecdotal evidence" that the in-vehicle display extension reduces each subscale, nausea (BF_{+0} = 0.72; $mean_{In-VehicleDisplayExtended}$ = 8.77, $sd_{In-VehicleDisplayExtended}$ = 9.73; $mean_{HMD}$ = 13.71, sd_{HMD} = 20.57), disorientation (BF_{+0} = 0.36; $mean_{In-VehicleDisplayExtended}$ = 18.86, $sd_{In-VehicleDisplayExtended}$ = 25.04; $mean_{HMD}$ = 23.35, sd_{HMD} = 29.50) and oculomotor disturbance (BF_{+0} = 0.43; $mean_{In-VehicleDisplayExtended}$ = 13.20, $sd_{In-VehicleDisplayExtended}$ = 13.03; $mean_{HMD}$ = 15.89, sd_{HMD} = 16.99).

Presence. Figure 15 illustrates the responses on the presence questionnaire, comparing the mean presence for in-vehicle display with passenger view extension and HMD-display. The analysis of the presence score reveals "no evidence" of increased presence by the extended in-vehicle display compared to the HMD-display (BF_{+0} = 0.064; ; $mean_{In-VehicleDisplayExtended}$ = 3.21,

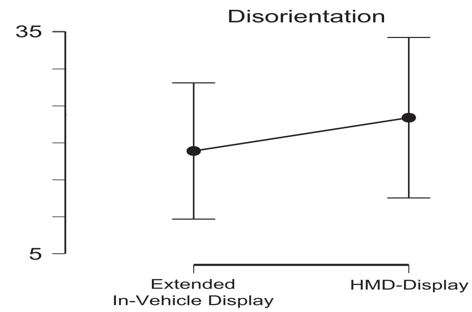

Figure 12: Disorientation comparing means and 95% credible intervals of in-vehicle display extension with the HMD-display

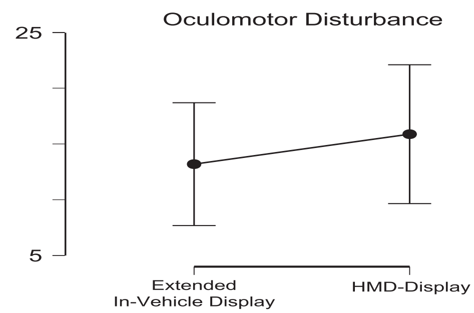

Figure 13: Oculomotor disturbance comparing means and 95% credible intervals of in-vehicle display extension with the HMD-display

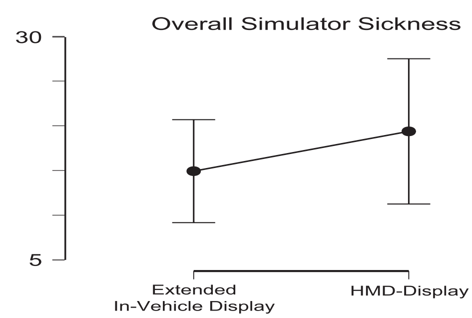

Figure 14: Overall simulator sickness comparing means and 95% credible intervals of in-vehicle display extension with the HMD-display

$sd_{In-VehicleDisplayExtended}$ = 1.04; $mean_{HMD}$ = 2.79, sd_{HMD} = 0.78). The effect is even reversed and reveals an "anecdotal evidence" for increased presence by the HMD-display compared to the extended in-vehicle display (BF_{-0} = 4.31).

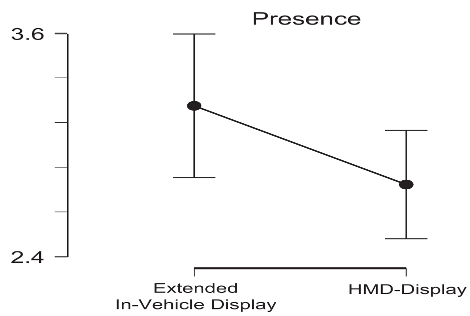

Figure 15: Presence comparing means and 95% credible intervals of in-vehicle display extension with the HMD-display

DISCUSSION AND CONCLUSION

This paper reports a novel visualization, using an in-vehicle windshield display and an additional passenger side window monitor in the VIL, for reducing simulator sickness and increasing interior interaction possibilities. On the one hand, the usage of the in-vehicle windshield display reduces technical implementation efforts (e.g., no head tracker needed) and improves fault tolerance for an incorrect settings. On the other hand, it reduces simulator sickness that recent research has shown to be a critical mitigating factor on user behavior in driving simulators [3, 5]. Respectively, this combines the reasons for favoring the use of a in-vehicle display based visualization over the use of an HMD-display in the VIL. Furthermore, the in-vehicle display based visualization can be further extended with a driver side window monitor to increase the field-of-view and resemble the real driving view in a virtual environment.

In this study, we showed that in-vehicle displays reduce overall simulator sickness as well as each of the subscales. Experiment 1 reports substantial evidence that the implementation of in-vehicle display can reduce all factors (nausea, disorientation, and oculomotor disturbance) of simulator sickness. The values of nausea, oculomotor disturbance, and the overall simulator sickness obtained in the HMD-display are in accordance with other studies like Karl et al. [12]. The simulator sickness scores using projection based visualization are lower compared to other driving simulators [1]. The cause for reduced simulator sickness could be a reduction of lag [25] and increased field-of-view. Furthermore, the reduction of simulator sickness is an extension of [25], who compared HMD-display and desktop displays of a static setup. For the second experiment we optimized the head position of the HMD-display. The optimization reduced the simulator sickness for HMD compared to Experiment 1 (nausea reduced by 232%, oculomotor disturbance reduced by 177%, disorientation reduced by 182%, and overall simulator sickness reduced by 192%). The reduction may be caused by more realistic optic flow [18] and may be exacerbated by a shorter exposure [8] in Experiment 2. Even though simulator sickness is asymptotic after 30min [26]. Although no evidence for a reduction of simulator sickness by the extended in-vehicle display compared to the HMD-display was found, overall simulator sickness reduced by 30%. In addition, means of each sub-scale are reduce (nausea by 56%, oculomotor disturbance by 20%, and disorientation by 24%). In summary, a optimization of the HMD-display could reduce simulator sickness. But the in-vehicle display (with and without passenger view) still reduces simulators sickness compared to HMD-display.

The implementation of an in-vehicle display, with and without the extension of a passenger view, did not change presence compared to an HMD-display. Comparing presence in Experiment 1 did show anecdotal evidence for increased presence by in-vehicle display. Comparing the presence score of Experiment 1 and 2 does not show differences. However, there is anecdotal evidence for decreased presence by the windshield projection in Experiment 2. This effect could be explained by either the different resolution between the windshield projection and the passenger view monitor. An alternative explanation could be an unnatural feeling with only a passenger side view but not driver side view. Nevertheless, these effects are small, and the presence scores are still good.

Overall, the results show, on the one hand, using a in-vehicle display reduces simulator sickness compared to an HMD-display. On the other hand, presence is not influenced by the implementation of an in-vehicle display compared to an HMD-display. In summary, using a windshield projection reduces implementation complexity, simulator sickness while delivering a high presence environment.

LIMITATION

The studies showed that the use of an in-vehicle display might increase behavioral validity. Furthermore, an in-vehicle display allows interaction with the interior. However, the types of scenarios that can be conducted (e.g., incursion by another vehicle from the side) can be limited. In Experiment 2, a passenger side window was used to solve some of this limitation. However, no driver window view was implemented. The driver window view may have a substantial impact on simulator sickness as it directly stimulates the peripheral view [4, 27].

One drawback of using a projection instead of HMD is possible issues with shadows/interference between the projector light and the steering wheel, or driver's placing their hands at the top of the wheel. This shadows may on the one hand decrease presence. On the other hand, possible information and cues may not be projected on the windshield.

Furthermore, the studies revealed a need to adjust the horizon of the windshield projection vertically. The need for adjustment may be increased for drivers of different height. To avoid a step in the visualization between windshield view and side view, the angles of the side windows must be precisely adjusted. This adjustment has turned out to be very difficult.

FUTURE WORK

This study focused on the psychological factors that are the foundation of driving performance measures. We showed that simulator sickness could be reduced with a in-vehicle display. However, in the next step a systematic characterization of driving performance metrics with both visualizations is necessary. The performance measures would further help to compare the external validity and identify the right simulation approach for each measure. Furthermore, the implementation of a driver side view is necessary and the next step. In addition acoustic simulation, such as environmental sounds generated by other road users, could be included. The addition of acoustic may increase presence [7, 32] and provide important cues to the driver.

Besides, the evaluated VIL may be an essential tool in the research on automated vehicles, which witnessed dramatic upsurge in recent years [17]. The VIL allows for experiments that can be highly controlled for the timing and presentation of events (e.g., handover, path trajectory, collisions). In addition, the VIL features realistic vehicle dynamics that recent research has shown to be a non-trivial mitigating factor on in-vehicle user behavior [19, 24]. Furthermore, a recent review on motion sickness in automated driving showed that motion sickness is a significant challenge [6]. The presented VIL may be used to evaluate mitigating factors of motion sickness, as it allows for experiments in a safe environment, but presents realistic vehicle dynamics.

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