Toward Immersive Self-Driving Simulations: Reports from a User Study across Six Platforms

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Figure 1. Which condition absorbs you the most? We implemented six autonomous driving simulation platforms with varying levels of visual and motion fidelity and tested their validity. (A. Computer Graphics VR + no Motion; B. Computer Graphics Multiscreen + Motion Platform; C. Computer Graphics VR + Motion Platform; D. Real-world MR + Motion Platform; E. Computer Graphics VR + Real Vehicle; F. Real-world MR + Real Vehicle)

ABSTRACT

As self-driving car technology matures, autonomous vehicle research is moving toward building more human-centric interfaces and accountable experiences. Driving simulators avoid many ethical and regulatory concerns about self-driving cars and play a key role in testing new interfaces or autonomous driving scenarios. However, apart from validity studies for manual driving simulation, the capabilities of driving simulators in replicating the experience of self-driving cars have not been widely investigated. In this paper, we build six self-driving simulation platforms with varying levels of visual and motion fidelities ranging from a screen-based in-lab simulator to the mixed-reality on-road simulator we propose. We compare the sense of presence and simulator sickness for each simulator composition, as well as its visual and motion fidelities with a user study. Our novel mixed-reality automotive driving simulator, named MAXIM, showed

highest fidelity and presence. Our findings suggest how visual and motion configurations affect experience in autonomous driving simulators.

Author Keywords

Autonomous driving; driving simulator; user studies; Immersive technology; mixed reality; on-road simulation

CSS Concepts

• Human-centered computing~Human computer interaction (HCI); User studies; Virtual reality;

INTRODUCTION

Human autonomous vehicle interaction research frequently examines user experience in self-driving cars or tests new in-vehicle interfaces. Conducting such tests in self-driving cars, however, presents significant regulatory and safety concerns. To circumvent these concerns, researchers often rely on driving simulators, which allow them to construct safe, ethical, replicable, and controlled environments [5]. For example, they have been used for research on take-over requests [4, 14], trust in autonomous vehicles [13], and driver behavior in self-driving cars [17]. They can also be used for the autonomous driving training, or preparing drivers for self-driving [39]. The primary dimension of validation for manual driving simulations is behavioral validity, or the extent to which driver behavior and performance in a simulation accord with

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those in a real car [26]. Measures for behavioral validity include driving speed and lane change behavior, among other in-vehicle behaviors [3, 25, 46]. Despite the value of self-driving simulations for human autonomous vehicle research [1] and the strong correlation between driver behavior and simulation fidelity [12], few studies have investigated their validity [19]. Therefore, our goal is not to assess driving behavior in self-driving simulations but rather to examine the simulations themselves. Our attention is to the extent user experience and user interface research in self-driving simulations yield the same result as in real autonomous vehicles. Therefore, we test how well simulations replicate sensory information and create the illusion of being in an autonomous vehicle. Our focus lies in the validation of autonomous driving simulations in terms of their fidelities, presence, and simulator sickness.

In this paper, we construct six different simulation platforms for self-driving research to explore the validity of self-driving simulations with varying levels of visual and motion fidelities. We assessed the fidelity of each simulation using visual and motion fidelities, a perceived or expected similarity to the corresponding reality [21, 42]. The simulators consist of either a real-world environment image or real-vehicle motion, and our novel simulator comprises both. Throughout this paper we propose a unique self-driving simulation validation method.

Prior studies have shown that higher sense of presence induces higher performance and simulation training effectiveness [40] and can mediate usability under driving simulation settings [31]. We thus set presence to be the primary dimension when assessing the relevance of a self-driving simulator and a real vehicle. Higher visual fidelities and the consistency of visual and motion fidelity yield better sense of presence.

We set simulator sickness to be another dimension of validation. Simulator sickness, a particular discomfort that arises during and after the simulation experiment [22], has a considerable effect on a person's mental and physical state during driving sessions [16]. Simulator sickness and its related discomforts can also confound experiment data [6], or interrupt human subject research, leading to the experiment drop-out [23].

RELATED WORKS

Self-Driving Simulator and On-Road Driving Simulator with Wizard of Oz Technique

Driving simulators range from low-cost simulators to high-cost simulators, with varying levels of visual, and mainly, motion fidelities. They enable verification of high risk scenarios or autonomous driving [11, 38]. Unfortunately, current autonomous technology cannot handle all factors of automation, so autonomous driving simulation is required [16].

One increasingly popular technique for autonomous driving simulation is the Wizard of Oz (WoZ) technique. WoZ ena-

bles implementation of computer systems beyond the technical constraints with an experimenter in-the-loop [7]. In WoZ experiments, a human experimenter (the “wizard”) operates a computer system without the knowledge of participants. The method allows HCI researchers to test user experience under various scenarios and circumstances. The method also has contributed to various Human-vehicle interaction (HVI) studies by creating the illusion of a self-driving car when the car was actually driven by a wizard [2].

Compared to in-lab simulators, on-road driving simulators create a more immersive experience by providing real-world sensory information, including real-world views and kinesthetic feedback. HVI researchers have proposed several WoZ ways of simulating self-driving cars to exploit the benefit of on-road simulators. First, Schmidt et al. applied the method to study human-machine interaction design considerations for future driver assistance systems [35]. To keep the illusion of the self-driving car, HVI researchers hid the driving wizard either under the seat [34] or behind the partition between the driver seat and the front passenger seat [2, 41]. The modified interior of the car, however, could lead to suspicion that the hidden human driver might be in control of the vehicle.

Despite their vivid experience, the number of scenarios tested with the on-road WoZ simulators does not compare to the in-lab simulators that only drive on real roads.

UX research for the technologies yet to be perfected has been facilitated in light of advances in immersive technologies. Hock et al. and McGill et al. first applied virtual reality technologies in a real moving vehicle [15, 24]. Goedicke and Ju et al. used similar technologies to build a WoZ autonomous driving simulator, the VR-OOM platform that connects the subject in a moving vehicle to a pre-constructed computer graphics environment in which the subjects cannot see the wizard driver [11].

Presence and Simulator Sickness

Presence is the subjective sense of belonging to an environment while physically located in a different space [36, 43]. High presence corresponds to a greater sense of belonging, whereas low presence indicates a diminished sense of belonging. In a virtual environment, presence is the sense of being situated within a computer graphic environment [43], and can thus also refer to a user's psychological state [26].

A high-quality simulation environment does not necessarily create high presence [28]. When the illusion created by the virtual environment collapses, called “break-in-presence,” the feeling of presence can be disturbed [18, 37]. When this happens, participants may experience simulator sickness, an illness that involves symptoms similar to motion sickness, and may lead to disruption of simulation experiments [6, 16].

Despite their similarities, simulator sickness and motion sickness differ in their symptoms and severities [6, 22], yet

both can be explained in part by sensory conflict theory. Sensory conflict theory describes motion sickness as a syndrome induced by either conflict between angular and linear vestibular systems, or between visual and vestibular systems [24]. On the contrary, simulator sickness is derived from the mismatch between visual and vestibular systems [22]. There are also other causes of motion sickness and simulator sickness such as postural instability [27] or specific movements [24].

Sickness induced by sensory conflict is particularly important in self-driving car studies since severity increases as drivers become inattentive to driving tasks or unable to predict motions of the vehicle [8, 24]. In scenarios where drivers read a book or otherwise do not pay attention to the road environment, motion sensed by their vestibular system may not coincide with their visual experiences. Likewise, passengers may suffer from motion sickness when they read a book or sit in the backseat [29]. Though self-driving cars may reduce sickness from oscillations by carefully designing driving strategies, drivers will compensate for this with increased sickness from sensory conflicts [8, 9].

To prevent break-in presence during simulation, an increased visual reality must be followed by an equivalent increased behavioral reality [28]. We, thus, set simulator sickness as a key dimension of evaluation for our comparative study, considering both its significance in long term use of simulations and importance in self-driving studies.

AUTONOMOUS DRIVING SIMULATION PLATFORM

We constructed six simulators with different visual and motion settings. The visual experience of the simulator spans from a monitor-displayed computer graphics (CG) environment, an HMD displayed computer graphics environment to HMD displayed real-world video streams. Additionally, we designed three configurations of motion cues. These include settings without motion feedback, with motion platform, and with real vehicle motion. We investigated how those different settings increase or decrease the validity of self-driving simulators in terms of fidelity, presence, and simulator sickness. Figure 1 illustrates the six different platforms and their visual, motion configurations, and Figure 2 shows their expected fidelities.

A. CG VR + no Motion (VR+nM)

In this simulation platform, participants wear a Virtual Reality Head Mounted Display (VR HMD) and sit on a fixed seat. Participants' viewpoint is from the driver seat of the virtual vehicle. Their visual experience includes a pre-constructed computer graphics virtual environment. No motion cues are provided during the simulation experience.

B. CG Multiscreen + Motion Platform (MS+MP)

This configuration is the most popular and commercialized setting. Participants do not wear a HMD but see the computer graphics environment on the screen, in which they are located in the driver seat. In our platform, the screen consists of three monitors. The motion platform gives kinesthetic

Figure 2. Six simulation platforms and their expected visual and motion fidelities.

feedback that corresponds to movement in the virtual environment.

C. CG VR + Motion Platform (VR+MP)

Participants wear a VR HMD and sit on a motion platform to experience virtual vehicle movements. In the computer graphics VR space, they are situated in the driver seat. While driving, they experience CG visuals and physical motion feedback from the motion platform.

D. Real-world MR + Motion Platform (MR+MP)

In this platform, participants wear a VR HMD and sit on a motion platform. Their visual experience includes a computer graphics-based virtual vehicle and real-world surrounding environments recorded on a real road. We thus call the platform ‘mixed-reality’. The platform gives kinesthetic feedback based on the real vehicle movement recorded simultaneously with the video. In this simulation configuration, participants see real images and feel motion cues provided by the motion platform.

E. CG VR + Real Vehicle (VR+RV)

We constructed this platform, following the work of Goedicke and Ju et al. [11]. In the platform, participants wear a VR HMD and sit in the front passenger seat of a real vehicle. The subjects see themselves sitting in a virtual vehicle, surrounded by a computer graphics environment. The virtual environment models the real-world space in the same size and reflects the movement of the real vehicle driven by wizard driver. Participants see a virtual environment while feeling real kinesthetic feedback of a real vehicle.

F. Real-world MR + Real Vehicle (MR+RV, MAXIM)

We introduce our new approach for mixed-reality automotive driving simulator, the MAXIM platform. We have discussed its initial concept in a conference workshop [44]. The platform simulates the experience of being in a self-driving car with mixed reality technologies and the Wizard-of-Oz method. Subjects wearing the VR HMD sit in the passenger

Figure 3. In-lab Driving Simulator Configuration.

seat of the real vehicle. In the virtual reality space, participants find themselves in the driver seat of the virtual vehicle. Participants thus experience the movement of the real vehicle during the simulation. The VR HMD, meanwhile, displays real road environments on the virtual screen that surrounds the virtual vehicle streamed from the front and rear 360-degree cameras. Participants, thus feel the illusion of being situated in an autonomous vehicle.

IMPLEMENTATION

Four In-lab Driving Simulators

The in-lab simulation platform comprises either multiple monitor displays or VR HMD and Motion Platform with a steering wheel attached. Using this platform, we constructed four different types of simulators (A. VR+nM; B. MS+MP; C. VR+MP; D. MR+MP), as shown in Figure 3.

Multiscreen

Multiscreen is a fundamental way of constructing the visual experience of immersive driving simulations. In our configuration, the screen consists of a flat 32-in monitor display with full HD (FHD) resolution at the center and two curved FHD 32-in monitors to either side. It surrounds the participants to help them better immerse into the simulation.

VR HMD and Computer

The Virtual Reality Head Mounted Display enhances immersion in virtual space by giving visual information to both eyes so that subjects see objects in the virtual space in three dimensions. We used Oculus Rift (1080 * 1200px, 110 degrees Field of View, 90Hz) and a high-performance PC (i7-8700K, GTX1080ti) to smoothly provide virtual reality images to the subjects and placed the VR tracking sensors in front of them to track head movement.

Motion Platform and Steering Wheel

The motion platform is a moving chair for the indoor simulation of kinesthetic feedback. It projects the virtual movement of the car into the physical space. We used two degree-of-freedom motion platforms A3 from Atomic to provide motion cues in indoor simulation configurations. Also, the

Figure 4. On-road Driving Simulator Configuration.

Figure 5. On-road Driving Simulator Diagram.

steering wheel was installed on the motion platform to enhance the sense of being in the vehicle.

Two On-road Driving Simulators

The on-road driving simulation platform consists of VR HMD, a real vehicle and dummy steering wheel, an On-Board Diagnostics version II (OBD-II), and a wizard driver. We built two different types of on-road driving simulations. One offers computer graphics visual experience in a real moving vehicle (simulator E. VR+RV). The other gives the visual experience of a real-world image streamed from 360-degree cameras and gives the visual experience of real-time image streaming (simulator F. MR+RV).

VR HMD and Computer

The use of virtual reality technologies in the real vehicle gives participants an illusion of sitting in the driver seat, though the participants are in the front passenger seat. We used the same VR HMD (Oculus Rift) as the in-lab simulator. We attached VR trackers on the windshield to cover the front passenger seat. Also, a high-performance laptop (Hansung BossMonster EX7989KFW) was used to stream VR and real images in a mobile environment. Due to the excessive power consumption of the laptop computer, a high capacity battery (1200W) was added to provide a stable power supply.

OBD-II

OBD-II is a sensor that reads physical data such as speed (RPM) from the vehicle. We used OBD-II to replicate the motion of the vehicle in the virtual reality space. We streamed OBD-II data in building the simulator E (VR+RV). We also logged OBD-II to build in-lab simulator D (MR+MP).

that replicates recorded visual and motion environments in-door.

360-degree Camera

We used two 360-degree cameras at the front and rear of the vehicle, as shown in Figure 4 and Figure 5, to collect visual information in all directions from one reference point. We streamed and recorded real-world environment images surrounding the vehicle. The front camera streaming forms surrounding environments while the rear camera builds side and rearview mirrors. We located the front camera directly in front of the windshield to offer the same spatial experience. The rear camera was attached to the rear windshield.

Wizard Driver in on-road driving simulators

The wizard driver plays the role of “wizard” from the Wizard-of-Oz method. The wizard driver has a driver’s license and plenty of real-world driving experience. An expert driver who practiced driving for enough time on the prescribed route controls the real vehicle of the on-road simulations on behalf of the machine intelligence in autonomous vehicles. This technique enables experiments under autonomous driving scenarios without safety concerns.

Real Vehicle and Steering Wheel

To fully exploit the benefits of real-world sensory information, we constructed two in-vehicle simulators for on-road experiments. The simulations with real vehicles provide the passengers with high fidelity motion feedback, as well as realistic vibrations and vivid audio cues. In on-road self-driving simulations, all systems were integrated into the real sports utility vehicle. We also installed a dummy steering wheel on the front passenger seat, where participants sit. We believe this helps participants immerse themselves better with the physical experience of touching and grabbing the steering wheel.

Simulation Environment

We implemented a simulation environment based either on computer graphics or real-road images. To compare simulators with natural contexts, we included two lane changes, four speed bumps, acceleration, and deceleration in the driving scenarios. The virtual reality road environment was modeled over a section of a university campus. On-road experiments are conducted on the same road as the virtual environment, as shown in Figure 8.

Computer Graphic based Simulation

Simulations with computer graphics environments are widely used across different disciplines for their potential in building an unlimited number of environments and scenarios.

As shown in Figure 6, we modeled a road in a university campus into unity environments with the same size. The course is 550m long in total. Buildings, trees, and other urban landscapes were replicated to offer realistic visual experiences. A side mirror and rearview mirrors were implemented to increase the visual fidelity of the simulation.

Figure 6. Computer Graphic based Simulation in Unity.

Figure 7. Mixed Reality with Real Images based Simulation in Unity

The subject’s point of view is on the driver’s seat of the virtual vehicle. The subjects can feel as if they’re in an autonomous vehicle. The movement of the virtual vehicle in unity was transferred to the motion feedback through the Simphynity, a custom software supported for the operation of A3 motion platform.

Real-image based Simulation (Mixed Reality Platforms)

To increase the visual fidelity of the driving environment, we used a video stream from 360-degree cameras attached on the front and rear of the vehicle. We built both in-lab driving simulations and in-vehicle driving simulations that provide 360-degree video visual experiences, as shown in Figure 7. The virtual screen that streams real-road environment surrounds the virtual vehicle in the VR environment, thus creating our ‘mixed reality’.

First, the in-lab mixed-reality simulator consists of the recorded 360-degree videos annotated with driving data. The visual experience is a real-world environment. However, motion fidelity is not as realistic as the real-road since the motions are replicated by a 2-axis motion platform.

We introduce a new simulator platform that streams the real-world environment surrounding a real moving vehicle. The video is streamed while a wizard driver drives the car. The HMD displays the streaming image as well as computer

Figure 8. Driving routes and driving scenarios for indoor (Map in Unity) and outdoor (Satellite Map) experiments. The red box is the start location and red line is the route.

graphics in the virtual vehicle. Participants sit in the driver seat in the mixed reality space.

EXPERIMENTAL DESIGN

Six autonomous driving simulations were designed, with varying degrees of visual and motion fidelities. To validate the six platforms, we conducted a user study with 20 subjects. Participant ranged in age from 20 to 31 ($M = 24$, $SD = 3.09$, 16 males, 4 females). We focused the user study on visual fidelities, sense of presence, and simulator sickness. Each simulation session took 15 minutes, including post-questionnaire. The entire experiment comprising the six simulator sessions lasted about 1.5 hours in total.

Procedure

To avoid the order effects in comparing the six simulations, we shuffled the order of simulations each participant experienced in a balanced Latin Square order.

In the case of the indoor experiment, four simulations were tested (A. Computer Graphics VR + no Motion, B. Computer Graphics Multiscreen + Motion Platform, C. Computer Graphics VR + Motion Platform, and D. Real-world MR + Motion Platform). Participants experienced driving about 0.55km straight from the starting point, as shown in Figure 8. Participants first had a simulator training session to adapt themselves to the simulation, alleviating simulation sickness [10, 16, 33]. They were allowed to freely explore the interior and watch the surrounding environment for about 1.5 minutes. The vehicle, then, started and drove 0.55km. The driving scenario consisted of deceleration and acceleration, four speed bumps and two lane changes.

For the outdoor experiments, two simulations were tested (E. Computer Graphics VR + Real Vehicle and F. Real-world MR + Real Vehicle). As shown in Figure 8, we drove about

0.55km, following the exact route as the indoor experiment. Participants had about 1.5 minutes of training for the outdoor simulations as well. After the training session, the wizard driver drove 0.55km. In the case of simulator E (Computer Graphics VR + Real Vehicle) the visual experience is identical to the in-lab simulator. In the case of the mixed reality outdoor simulator F (Real-world MR + Real Vehicle), the subjects could see the real-time streaming of road environments.

After each simulation, participants rested until they didn't feel any sickness or fatigue then were asked to answer post-questionnaires assessing their visual, motion fidelities, presence, and simulator sickness.

Simulator Sickness Questionnaire

We measured subjects' simulator sickness degrees using the Simulator Sickness Questionnaire (SSQ) [22]. Participants were asked to rate their experience of 16 symptoms on a scale of 0-3, to assess subscores regarding nausea (N), oculomotor related discomfort (O), and disorientation (D).

The 16 SSQ symptoms comprise general discomfort, fatigue, headache, eye strain, difficulty focusing, increase salivation, sweating, nausea, difficulty concentrating, fullness of head, blurred vision, dizzy (eyes open), dizzy (eyes closed), vertigo, stomach awareness, and burping. The subscore Nausea is influenced by the symptom items general discomfort, increase salivation, sweating, nausea, difficulty concentrating, stomach awareness, and burping. Oculomotor-related subscores comprise the symptom items general discomfort, fatigue, headache, eye strain, difficulty focusing, difficulty concentrating, and blurred vision. Disorientation-related subscores comprise the symptom items difficulty focusing, nausea, fullness of head, blurred vision, dizzy (eyes open), dizzy (eyes closed), and vertigo.

Figure 9. Visual and Motion fidelity, Presence, Simulator Sickness of six self-driving simulations. t-test baseline: simulator B (MS+MP). *: $p < .05$, **: $p < .01$, *: $p < .001$**

To compute the scaled scores, 16 symptom scores were multiplied by unit weight, and the weighted scores were added to get the weighted total. The subscores were then calculated by multiplying appropriate modulus to the weighted totals (N: 9.54, O: 7.58, D: 13.92). The total score (TS) was acquired from every weighted total using the total score transformation ($TS = (\text{Sum of three weighted totals}) \times 3.74$) [22].

Visual and Motion Fidelities

We designed single-item questionnaires assessing visual and motion fidelities. Participants were asked to freely rate their subjective experience of visual and motion fidelities of each simulation on a scale of 0 to 10. As to visual fidelity, we asked, “Was the visual experience in the simulator realistic? (e.g., graphic of the road environment, graphic of the vehicle)”. As to motion fidelity, we asked, “Were the motion, vibration, and kinesthetic feedback in the simulation realistic? (e.g., physical feedback in the situation of acceleration, deceleration, and lane change)”.

Presence Questionnaire

We asked participants to rate their feeling of presence in each simulation platform through Witmer and Singer’s presence questionnaire version 2 [43], with a 7-point Likert scale. The subscales and items in the questionnaire were partially adapted and modified to suit our self-driving simulation platforms. In detail, involvement and control (INV/C items 2, 5, 10, 13, 14, 18, 23, 25, 26, 27, 32 from W&S), natural (3, 7, 12), auditory (6, 15, 16), resolution (19, 20), and interface quality (28) were examined as subscales of presence. Items not related to the driving simulations were excluded from the questionnaire.

RESULT

Figure 9 illustrates the perceived visual and motion fidelities, presence, and simulator sickness of each simulator. The results of repeated measure ANOVA indicate that there was a

significant effect of simulator type on the visual fidelity, motion fidelity, presence, and simulator sickness; $F(3.6, 68.41) = 7.374, p < .001$, $F(5, 95) = 17.272, p < .001$, $F(5, 95) = 18.269, p < .001$, and $F(5, 95) = 7.374, p < .001$, respectively. The degrees of freedom for visual fidelity have been corrected with Greenhouse-Geisser estimates ($\epsilon = .53$) since Mauchly’s test shows the assumption of sphericity had been violated, $\chi^2(5) = 24.632, p = .040$. The colored asterisks above the bar graphs show their significance of pairwise t-test compared with the baseline simulator (simulator B).

Perceived Fidelities

Among six driving simulators, simulator F, the MAXIM platform that supports on-road experiment with video see through mixed reality, showed the highest score both for visual and motion fidelities. On the other hand, Simulator A, configuration of which comprised VR HMD display without motion feedback recorded the lowest both for visual and motion fidelities.

Visual Fidelity

In detail, our in-vehicle MR simulator (simulator F, MAXIM) scored the highest visual fidelity among six platforms, at 23.2% higher than baseline; $t(19) = 3.310, p < .01$. The other MR platform, simulator D, was also perceived to have significantly higher visual fidelity than baseline; $t(19) = 2.622, p < .05$. The VR simulator without motion cues (simulator A), on the other hand, had the lowest visual fidelity: 10.9% lower than baseline.

Motion Fidelity

Among six simulation platforms, the mixed reality simulator with real vehicle motion (simulator F) ranked highest in motion fidelity, 39.3% higher than the baseline; $t(19) = 4.155, p < .001$. Simulator C was also reported to have 17.2% higher than baseline with significance; $t(19) = 2.221, p < .05$. The simulator without motion cues (simulator A) showed the

lowest motion fidelity, 52.5% lower than baseline; $t(19) = -5.040, p < .001$.

Total Presence

Our novel simulator F, which showed the highest visual and motion fidelities, were evaluated to support the highest sense of presence, 30.5% higher than baseline; $t(19) = 5.200, p < .001$. Simulator F is followed by the other mixed reality simulator (simulator D), scored 15.7% higher presence than baseline with significance; $t(19) = 2.817, p < .05$. Likewise, simulator A, which was assessed to have the lowest visual and motion fidelities, showed the lowest presence. Simulator A was the only platform that had less presence than baseline, which showed 13.3% and significantly lower score; $t(19) = -2.275, p < .05$.

Simulator Sickness

The baseline simulator (simulator B), which does not use VR HMD, showed the lowest total sickness score. Simulator E scored the highest simulator sickness, approximately 3.7 times higher than baseline with significance; $t(19) = 3.533, p < .01$. Simulator A, which lack motion feedback induced the second highest simulator sickness, significantly higher than baseline; $t(19) = 2.880, p < .01$. The two MR simulators, D and F, also showed higher sickness than baseline; $t(19) = 2.549, p < .05$ and $t(19) = 2.208, p < .05$, respectively.

Effects of Motion Configurations

No Motion vs Motion Platforms

The existence of motion feedback significantly increased visual and motion fidelities and presence and significantly decreased simulator sickness. Comparing simulator A and C, motion generated by the motion platform significantly increased both visual and motion fidelities; $t(19) = 2.396, p < .05$ and $t(19) = 9.277, p < .001$, respectively. The existence of motion that matches visual change consequently increased presence at a significant level; $t(19) = 5.233, p < .001$, while significantly reducing simulator sickness; $t(19) = 2.319, p < .05$.

Motion Platform vs Real Vehicle

Using a real vehicle instead of a motion platform increased motion fidelity and presence only when the visual configuration was real-world image. Comparing simulators D and F, the use of a real-vehicle significantly increased both motion fidelity and presence; $t(19) = 2.275, p < .05$ and $t(19) = 2.947, p < .001$, respectively. However, comparing simulators C and E, where visual configurations are set to be computer graphics VR, no significant difference in visual and motion fidelities, presence and simulator sickness were reported between motion platform and real-vehicle motion configurations.

Effects of Visual Configurations

Multiscreen vs VR HMD

Comparing simulators B and C, the use of VR HMD increased the motion fidelity at a significant level; $t(19) = 2.221, p < .05$. However, no significant increase in visual fidelity,

presence, and simulator sickness were found between multiscreen and VR HMD.

Computer Graphics VR vs Real-road Image MR

The use of Real-road image MR, instead of computer graphics VR, significantly increased visual and motion fidelities and presence while significantly reducing simulator sickness only when equipped with real vehicle motion configurations. Comparing the two in-vehicle simulators E and F, real-road image view was assessed to have better visual and motion fidelity; $t(19) = 5.280, p < .001$ and $t(19) = 4.416, p < .001$, respectively. Real-road image also outperformed computer graphics in the dimensions of presence and simulator sickness; $t(19) = 4.734, p < .001$ and $t(19) = 2.114, p < .05$, respectively, when provided with real-vehicle motions. However, comparing simulators C and D, where participants sat in the motion platform, no statistically significant difference was found in visual and motion fidelities, presence, and simulator sickness.

DISCUSSION

Practical Considerations

Our study on the validity of six simulators suggests which configuration should be selected for specific research goals. In general, using VR HMD induced higher fidelity and presence while screens had benefits of lower simulation sickness. Providing pertinent motion relieved sickness while increasing overall presence. The simultaneous use of natural visual and motion experience also increased visual and motion fidelities and the sense of presence. However, the disparity between the motion perceived from a subject's visual cognition system and that from the vestibular system resulted in "break-in-presence", which decreases presence of the simulation environment and increases simulator sickness [24, 28].

Our pairwise comparison suggests that visual and motion cues should be designed to be consistent with each other. Real car motion makes the simulator have a high presence when used with real-world streaming, but not as much when applied to graphical environments (*simulator F. MR+RV vs simulator E. VR+RV*). When visual experience includes a real-world environment, real vehicle motion cues generated higher presence than artificial motion cues from a motion platform (*simulator F. MR+RV vs simulator D. MR+MP*). Using a motion platform in a computer graphics environment significantly increases presence while reducing simulator sickness (*simulator A. VR+nM vs simulator C. VR+MP*). However, when the visual experience is filled with artificial graphics, real vehicle motions do not significantly increase presence (*simulator A. VR+nM vs simulator E. VR+RV*).

For validation, this study is the first comparative evaluation of results over the six platforms. The novel self-driving *simulator F (MAXIM)* was first introduced and evaluated through this study and showed the highest visual and motion fidelities and presence, and relatively low simulator sickness. Specifically, practical considerations for each simulator can be summarized as follows:

The first considerations concern two simulators that are commonly used in non-self-driving situations. *Simulator B* (MS+MP) will be pertinent for studies where participants should be free from potential physical discomfort by VR HMD, except for studies that necessarily employ a bar-type eye-tracking system where motion-induced missing and erroneous data is hard to process. *Simulator B* also minimizes simulator sickness in participants. *Simulator C* (VR+MP) will provide high presence in self-driving situations and low simulator sickness, guaranteeing more continuous and reliable tracking of a driver's eye-gaze fixation states (similar to *simulators D, E, F*). In general, the simulator is easier to implement for many cases of simulated self-driving than building a CG driving environment (similar to *simulators A, B, E*). This could also result in varying driver experience due to different and less natural motion fidelity across different motion systems (similar to *simulators B, D*).

The second considerations concern three simulators that can be used in autonomous driving situations. *Simulator D* (MR+MP) allows a safe, indoor, exactly-reproducible MR experiment for risky, challenging, or experimental self-driving scenarios while immersed in photo-realistic, outdoor environments with a full inclusion of visual-distractive factors. The simulator fits better with studies investigating individual differences with regard to "repeated" photo-realistic self-driving situations that the other MR *simulator F* with a wizard driver cannot provide.

Simulator E enables VR driving simulation in a vehicle as it travels on a road. This platform provides study participants rich motion sensation and ambient sound from actual road driving, which other indoor self-driving simulators cannot (similar to *simulator F*). Nonetheless, studies using this platform should necessarily discuss potential issues caused by the perceptual discrepancy between perceived visual fidelity and perceived motion fidelity (similar to *simulator D*).

The novel *simulator F* (MAXIM) allows participants to engage in one of the most realistic self-driving environments in mixed-reality technology, and is probably the only platform that allows studies on naturalistic interactions between the real-world environment and study participants. We can incorporate natural reactions of pedestrians and other adjacent cars, for instance, to study participant's actions. The simulator is, thus, free from the potential perceptual discrepancy between perceived visual fidelity and perceived motion fidelity, and shows lower simulator sickness compared to the other in-vehicle simulator (approx. 37% lower than *simulator E*). *Simulator F* (MAXIM) is also further applicable toward collecting participants' experience annotated with their physiological responses, real-world environment view, driving status, and corresponding geographical data from self-driving sensors, while it is driven safely by a wizard driver. The results hypothesized that *Simulator F* (MAXIM) may provide the best self-driving simulation fidelity across four fidelity dimensions defined by Rhemann and Reiner [30, 32].

Limitations and Future Works

Our study has assessed visual and motion fidelities of simulators with limited dimensions. Among four dimensions of validity discussed by Rhemann and Reiner [30, 32], including equipment fidelity, environmental fidelity, objective fidelity, and perceptual fidelity, we only evaluated perceptual fidelities of different simulators, which is associated with the degree to which participants perceive the simulation as real-world driving. Also, we used a one-question survey for the measurement of perceptual fidelity to see how our participants perceived the visual and motion fidelity of the six simulators. We aimed to capture participants' initial thoughts of the platforms in the two fidelity aspects by asking a single direct question. However, this questionnaire lacks sufficient validation of the question.

The study also contains limited levels of fidelities. Motion platform is discussed as a single binary variable in the paper, but fidelities of motion platforms vary depending on whether the platform is fixed base or moving base. The fidelities of motion platforms are also affected by the degrees of freedom the system supports. We also didn't include a real self-driving car as a control condition or a more dynamic self-driving situation in the fidelity validation.

The validity of the study results applies to specific applications which require presence, low simulator sickness, and/or perceptual fidelity, especially at the binary variables of realism in visual and motion simulation. Behavior validity, which is a common dimension in non-self-driving studies were not included in our research [45]. The validation study, thus, can be further enriched by adding other dimensions including driver's behavior and affective states into the comparative evaluation across six platforms. Despite concerns that drivers might not behave the same in the simulator as in the real autonomous vehicle, simulators are the only way to study driver behavior in self-driving car without risk of hazardous situations. Future works exploring the validity of different simulators in terms of driver's behavior or psychological states such as response time in take-over request, driving performance immediately after take-over, situation awareness, perceived danger, and trust will further enrich the comparative study.

CONCLUSION

In this paper, we compared the validity of six self-driving simulators with different visual and motion configurations. Prior work on the validity of manual driving simulators has focused on the consistency of driver behavior and performance. Thus, it is difficult to apply the same method to the validation of autonomous driving simulators. This is the first work on the validity of self-driving simulators, and it included two on-road simulators. Given the research usage of self-driving simulators, we set visual and motion fidelities, presence and simulator sickness to be the dimensions of validation. Our pairwise comparisons suggest how to design valid self-driving simulators to yield simulators with better

presence and lower simulator sickness. The use of virtual reality induced increased visual and motion fidelities. The multiscreen and motion platform based simulator was rated to have the lowest simulator sickness. Meanwhile, the in-vehicle simulation platform with video-see-through streaming of real-road environment, the MAXIM platform we propose in this paper, ranked highest on visual and motion fidelities and sense of presence. Our main finding includes how visual-motion cues influence the sense of presence and simulator sickness.

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