Are Head-mounted Displays Really Not Suitable for Driving Simulation? A Comparison with a Screen-Based Simulator

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***Abstract*—Head-mounted displays (HMDs) are considered a promising, highly immersive display technology, which has been widely discussed in the context of driving simulation. The literature is heterogeneous to date with regard to the effects of HMDs on simulator sickness, the sense of presence, and perception. In the present study, a comparison between a modern HMD with a screen-based (LED wall) simulator is conducted in a repeated-measures driving simulator study including *N* = 31 subjects. The results indicate that the HMD is neither better nor worse, but performs equally well as the screen-based simulator in terms of simulator sickness, presence, and active distance perception. Evidence for passive distance and speed perception was only anecdotal, though also mostly points at a null-effect. The only (anecdotal) evidence of worse performance in the HMD simulator was in an active braking task. Accordingly, the present study did not identify disadvantages of using current HMDs in driving simulation.**

***Index Terms*—driving simulation, virtual reality, head-mounted display, simulator sickness, presence, perception**

I. Introduction

In driving simulation the goal is usually to provide the driver with a realistic impression of the displayed scene. Human perception and information processing are central in this context. A driving simulator is required to correctly reproduce sensory inputs received by the driver [1].

Visual information is key to the driving task [2]; **distance** [3] and **speed perception** [4] are especially important as they are required for tasks such as stopping, overtaking, or maintaining speed. Both are based on visual input information [5]. Regarding distance perception, pictorial cues and binocular cues can be distinguished. While pictorial distance cues, such as the relative size of objects or occlusion, are comparatively easy to implement, binocular cues are more difficult to reproduce. Convergence is a binocular depth cue which refers to the angle at which the eyes are relative to each other when focusing [6]. However, this is thought to be relevant only at very short distances of 2-3 m. Accommodation refers to the contraction of the ciliary muscle. In a moving environment, also motion-dependent cues influence depth perception, such as motion parallax: Objects which are closer to the observer seem to move faster than objects in a far distance [6].

When it comes to speed perception, optic flow is believed to be the main determining variable. It is generated by the motion of an observer and his surroundings. When driving and looking in the direction of travel, environment objects seem to move out of the central field of view (FOV) into periphery [6]. The faster objects move along the optic flow, the faster the intrinsic movement is perceived. Summarizing the information presented above, visual perception undoubtedly determines driving behavior. Driving simulators should replicate real-world driving behavior as good as possible (also referred to as *behavioral validity* [7]), as only then it is possible to draw inferences on the real-world context.

Visual perception is largely determined by *simulator fidelity*, which is commonly understood as the capability of the simulator to reproduce the real-world driving context [7]. Display hardware can contribute to the correct representation of real-world cues or its deterioration [5]. Both software and hardware elements determine visual fidelity. As the present study is aimed at investigating influences of the display type, we will focus on effects of the hardware technology.

A. Display technologies in driving simulators

Among the most frequently used display solutions in driving simulators are screens (mostly LCD panels), projectors, or

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head-mounted displays (HMDs). HMDs offer a cheap solution as all elements of a real vehicle can be displayed virtually, hence no physical mockup is required. [8] proposed that 40 % of the studies could be conducted using HMDs. They mention as a benefit that HMDs are, at least partially, able to provide binocular depth cues. Perception may thus be enhanced with HMDs. McIntire et al. concluded in their 2014 review [9] that 60 % of the studies show beneficial effects of binocular displays. However, [10] proclaim that the mere fact that a three-dimensional world is transferred to a two-dimensional sort of display leaves room to ambiguity. Even state-of-the-art stereoscopic displays are incapable of delivering an appropriately variable focus, and thus, provide vergence cues without an adequate accommodation, causing a vergence-accommodation conflict.

[8] also state that the **sense of presence** should be increased with HMDs, which was also reported by [11]. The sense of presence is defined as the sense of being there in a virtual environment [12]. It is assumed to depend on immersion, which in turn is understood as the degree to which the real-world is shut out by a setup [13]. The higher the sense of presence, the more realistic drivers are expected to behave within the virtual environment [11]. The literature on effects of using HMDs on presence is ambiguous, however, as effects could not be confirmed by all studies [14], [15].

The incidence of **simulator sickness** is often reported to be increased with HMDs [11], [15]–[17], forming a potential disadvantage. Simulator sickness is a physical discomfort that can occur when the cues received in a virtual environment do not match the receiver's expectations [18]. Sickness is to be reduced to minimize dropouts and preserve validity [19], [20]. Also regarding simulator sickness, effects of HMDs have not been fully elucidated. [14] and [21] could not confirm any effects of using HMDs on sickness. [22] even found increased sickness in projection screens when compared to HMDs.

Besides mere display effects, there are some practical implications when using HMDs. Firstly, when wearing HMDs, participants are always exposed to extra weight and often extra cables, which can lead to an unnatural feeling and less head movement. Second, the FOV is limited with HMDs (approx. 110° with most to-date HMDs, approx. 200° in the real world [23]), potentially reducing optic flow, while peripheral information is available with other displays. We also found that many research papers on HMDs are comparatively old or used low-fidelity HMDs, which is often associated with lower resolution [8], contrast, FOV, etc. Thus, the differences found between HMDs and other displays may also be attributed to other hardware properties. The horizontal FOV, for instance, was reported to influence presence [24], simulator sickness [25], distance and speed perception [5], [26]. Resolution can influence distance perception by atmospheric depth [27]. Optic flow should also depend on the horizontal FOV [6].

Another limitation of previous studies is that there were differences in the display technologies compared (projection: [14], [15], [22]; displays: [11], [28]). When multiple screens are combined, display boundaries are usually visible, which may reduce the immersion of the visualization. Projection systems, on the other hand, are often low-contrast, which can also have a negative impact on immersion. In the present study, we therefore compare an HMD to a highly immersive and novel visualization technology in driving simulation: the LED wall. LED walls are commonly used in advertisement or in television studios. Smearing effects can be reduced at low latency and realistic blending can be realized, which is a common issue with projectors. Furthermore, due to the high image contrast of the LED technology, it is possible to reproduce colors and lighting conditions more realistically.

B. Research gap

In summary, HMDs offer a cheap and easy solution for visualizing driving scenes and thus hold great potentials for driving simulators. Findings on effects of using HMDs, however, are so far ambiguous and require clarification. Studies that did not find effects of HMDs did not provide statistical evidence for the equivalence of different visualization systems. Using Bayesian hypothesis tests instead of frequentist statistics (see section "Statistical analysis"), we aim to address statistical equivalence in the present study to identify whether there is really no disadvantage in using HMDs.

Many studies have been conducted with outdated HMDs, which were also disadvantageous in terms of hardware aspects beyond the display type. For the reasons outlined above, we conducted a new comparative study of a state-of-the-art HMD with an LED wall. As described above, the LED wall technology is rather new in the context of driving simulation and has therefore not been included in previous investigations.

C. The present study

A within-subject study was conducted in which subjects experienced an LED wall simulator and an HMD simulator in succession in different scenarios. We applied the following hypotheses:

H1: Distance perception is more accurate in the HMD simulator due to the availability of binocular depth cues.

H2: Speed perception is more accurate in the LED wall simulator due to a larger FOV and peripheral vision.

H3: The sense of presence is higher in the HMD simulator.

H4: Incidence and severity of simulator sickness are higher in the HMD simulator.

II. Methodology

A. Sample

Out of the initial sample, 22 participants dropped out, 6 of them for technical reasons. Another 16 participants dropped out due to simulator sickness; 9 while using the HMD simulator, and another 7 while using the LED wall simulator. 31 participants completed the study, of which 3 were female and 28 were male. Participants were aged between 20 and 57 years, with an average age of 31 years.

B. Materials

The software Unreal [29] was used for visualization. Object and agent information and trajectories were provided by proprietary software modules. Hardware components and software integration of the actuators were largely standardized among the mockups. The frame rate was limited to constant 60 Hz in both simulators to avoid fluctuation. The achieved contrast of the HMD using OLED technology is comparable to that of the LED wall (approx. 1,000,000:1). A limitation was that the brake in the VR simulator worked using a force sensor while the brake in the LED wall simulator worked using a stroke sensor. The brakes were manually calibrated to ensure the same braking response and effect in both simulators.

The **HMD simulator** (Figure 1) consisted of a seat box from a BMW 5-series vehicle. A matching design model was displayed in the virtual scene. For visualization, the Varjo VR-3 was used. According to Varjo [30], the VR-3 offers the highest resolution as well as one of the widest FOVs (1920×1920 px per eye and 115°) on the market. The VR-3 should therefore deliver the fairest possible comparison. The VR-3 has a total weight of 944 g. In the present implementation, participants were unable to see their hands.

The **LED wall simulator** (Figure 1) was equipped with a full-vehicle BMW 5-series mockup. The simulator motion system was disabled to allow comparability with the static HMD setup. The LED wall offered a 310° horizontal FOV, with an overall resolution of approximately 26 pixels per degree. Rear vision was implemented with LCD display mirrors.

C. Design

The present study was performed as a 2×4 within-subjects design including the factors driving simulator (HMD vs. LED wall) and scenario (country road, highway, test track, urban). The country road scenario was always presented first. The remaining scenarios were presented in a counter-balanced order. The order of presentation was the same in the two driving simulators (for each participant). The order of the driving simulators was also balanced to prevent order effects.

1) Dependent variables: Distance and speed perception were measured by verbally provided open estimates. Simulator sickness was measured using the single-item Misery Scale (MISC [31]). Presence was measured using an adaption of the Slater-Usoh-Steed questionnaire for driving simulators [32].

Fig. 1. Illustration of the two simulators. HMD = left, LED wall = right.

2) Statistical analysis: All hypotheses were formulated in a directed manner based on existing literature. However, the study situation was heterogeneous and partially contradictory. To account for this, all results will be evaluated based on Bayesian hypothesis testing. In contrast to the frequentist approach, Bayesian statistics allow statistical support for both difference and equivalence hypotheses. The Bayes factor is a relative indicator of the probability of the observed data given equivalence or an effect and can be interpreted according to the recommendations provided by [33]. It should be noted that Bayes hypothesis tests, despite their advantages, have so far rarely been used in research, which may hinder the comparability with results of other studies.

D. Procedure

The drives were performed subsequently with short questionnaires after each scenario. The **country road** scenario served as an introductory drive. The **highway** scenario included different tasks related to distance and speed perception. The distance-related tasks followed a three-stage scheme, in which there was always a vehicle driving in front. In the first task (*blind following task*), the vehicle in front was driving at a speed of 92 km/h and participants were instructed to follow it in a constant distance of 50 m and to let the experimenter know when they thought to have the correct distance. The actual distance was considered as an indicator of *active*, i.e., perception with regulation effort, *distance perception*. Second (*blind distance keeping task*), participants were supported to achieve the correct distance of 50 m, and were then instructed to keep this distance as accurately as possible for one minute. No speedometer information was available in the first two tasks. The standard deviation of the distance to the vehicle in front was considered as an indicator of *active distance perception*. In the third task (*acceleration task*), speedometer information was available. This task was instructed exactly the same way as the second, with the only difference that the driving speed of the vehicle in front changed from an initial speed of 92 km/h to 105 km/h. The point of ego-vehicle acceleration over 95 km/h was considered as an indicator of *active speed perception*. For the *passive speed perception task*, again no speed information was available to the participants. An automated drive was carried out with a driving speed of 137 km/h and participants were asked to estimate the driving speed. The provided estimate was considered as a measure of *passive speed perception*. In the **test site** scenario, again distance perception was investigated. First (*egocentric distance perception task*), participants were asked to estimate their egocentric distance to a person placed next to a cone in a distance of 50 m, 70 m, or 120 m, with each distance presented twice in a randomized order. A cone at a distance of 20 m was always given as a reference. The distance estimates are indicators of *passive distance perception*. Second, there was a *target braking task*, in which participants were asked to come to stop at a designated position marked by cones and an adjacent vehicle. The distance to the stopping line was interpreted as an indicator of *active distance perception*. Last, in the *urban task*, participants were navigated through a large city on specific routes. The urban scenario included different types of road users, such as other vehicles or bicyclists, and active traffic signals. Typical of urban traffic, it included a lot of stopping and turning. Sickness and presence were assessed after each scenario.

III. Results

All Bayesian analyses were performed using the software JASP [34]. Default priors [35] were used, as based on the mixed study situation no concrete priors could be formulated. The Bayes factor analyses included the factor driving simulator (HMD vs. LED) in each case, and another trial/scenario factor where applicable (for: egocentric distance perception, target braking, simulator sickness, sense of presence).

A. Perception

In the blind following task, the Bayes factor analysis indicated moderate evidence for equivalence across the two driving simulators regarding the distance to the vehicle in front BF_{incl} = 0.26, Figure 2. In the blind distance keeping task, moderate evidence for equivalence was found for the standard deviation of the distance to the vehicle in front, BF_{incl} = 0.27, Figure 3. The analysis of the acceleration task indicated moderate evidence for equivalence in the time to react to the accelerating vehicle, BF_{incl} = 0.26, Figure 4. In the passive speed perception task, the analysis yielded weak evidence for equivalence, BF_{incl} = 0.74, Figure 5. The analysis on the accuracy of the passive distance estimates provided throughout the egocentric distance perception task was performed including the factor trial in the null model, as there was no hypothesis on the impact of trial. The analysis indicated weak evidence for equivalence across the simulators for the 50 m distance, BF_{incl} = 0.61, the 70 m distance, BF_{incl} = 0.37, and the 120 m distance, BF_{incl} = 0.32 Figure 6. In the target braking task, there were three trials, yet the effect of trial was again not relevant to the specified hypotheses and was therefore included in the null model. The analysis indicated weak evidence for a worse performance in the HMD simulator, BF_{incl} = 1.87, Figure 7.

B. Simulator sickness

The simulator sickness analysis indicated moderate evidence for the absence of an effect of the driving simulator, BF_{incl} = 0.24, and strong evidence for an effect of the driving scenario, BF_{incl} = 1156.81 (Figure 8). Bayesian post-hoc tests pointed out that significantly more simulator sickness was induced in the urban scenario compared to all other scenarios. There was no interaction of visualization technology and scenario, BF_{incl} = 0.09 (Figure 8).

C. Presence

Presence was analyzed including the factor driving scenario. The analysis indicated moderate evidence for the absence of

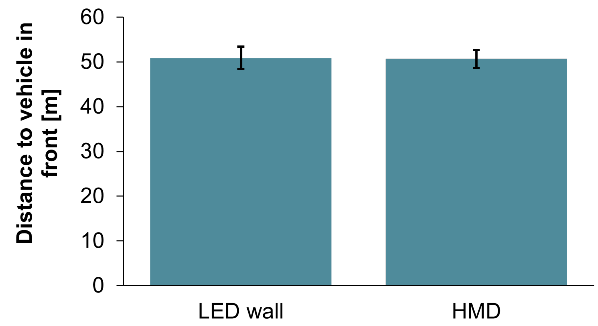

Fig. 2. Descriptive statistics for the blind following task. Error bars indicate standard errors of the mean.

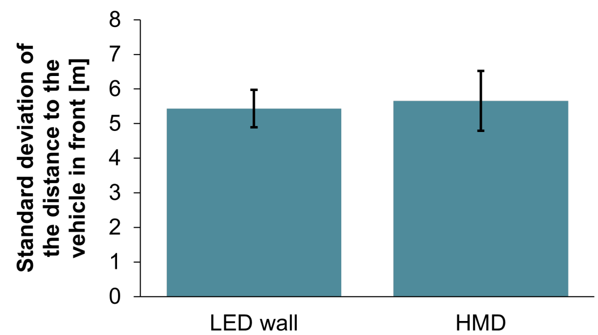

Fig. 3. Descriptive statistics for the blind distance keeping task.

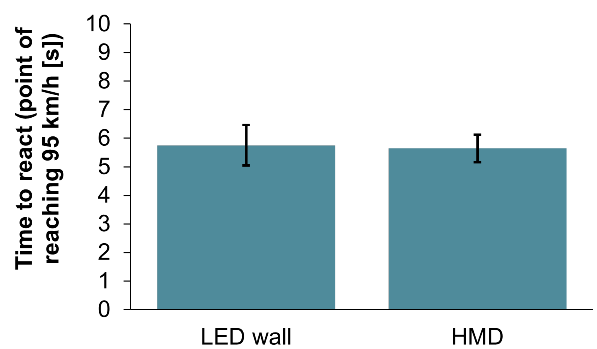

Fig. 4. Descriptive statistics for the acceleration task.

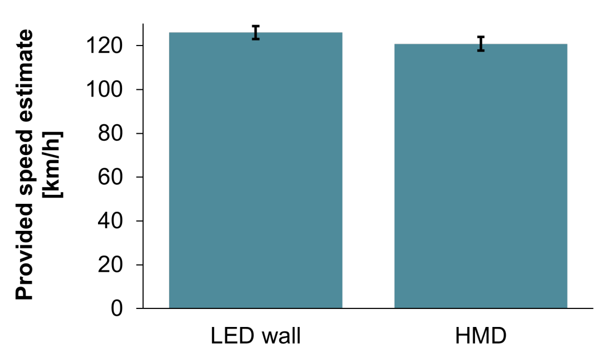

Fig. 5. Descriptive statistics for the passive speed perception task (highway).

an effect of the factor driving simulator, $BF_{incl} =$ 0.24, strong evidence for the absence of an effect of the driving scenario, BF_{incl} = 0.07, and strong evidence for the absence of an interaction of simulator and scenario, BF_{incl} = 0.04 (Figure 9).

IV. Discussion

In the present study, an HMD and an LED wall simulator were compared with regard to possible differences in perception, simulator sickness, and presence. Contrary to our expectations, no positive effects of HMD use on distance perception and no negative effects on speed perception were observed. There was moderate evidence for equivalence across the two simulators in the blind following and distance keeping tasks as well as in the acceleration task. In the passive speed and egocentric distance perception tasks, we found anecdotal evidence for equivalence. In the target braking task, there was anecdotal evidence for a better perception in the LED wall simulator. The distance estimation tasks on the highway and the egocentric distance perception tasks were mainly concerned with longer distances, where binocular cues tend not to play a role. For this reason, the stereoscopic presentation in the HMD hardly provides an advantage here, which is why the absence of an effect is not too surprising, even though positive effects might have been expected due to the lower distance to the display in the HMD simulator. It was rather unexpected that the LED wall performed better in the braking task, considering that small distances ($<$ 10 m) matter here (hence binocular cues matter) and the display is closer in the HMD, reducing the conflict of focusing distance (display) and presented distance. However, the evidence was only anecdotal. Note that the tasks applied for distance and speed perception were rather simplistic, including, e.g., only one reference vehicle in the following task with no other surrounding traffic. More complex tasks may provide more elaborate results, though are also more difficult to interpret.

Regarding speed perception, positive effects of the LED wall simulator were expected due to the wider FOV, which was not confirmed. [5] suggested that a 120° horizontal FOV would be required to correctly perceive speeds. The HMD simulator offered a FOV (115°) that was already very close to this, so the difference may simply not have been large enough.

There was evidence for equivalence across the two simulators with regard to the incidence and severity of simulator sickness, which did not match our initial expectations. However, other authors could neither identify any negative effects of HMD usage [14], [21], [22]. Furthermore , the present study used a state-of-the-art HMD, which was not the case in most previous investigations. Effects found in earlier studies could also be attributable to other properties of the used HMDs, such as low resolution. There was also a scenario effect: simulator sickness in the urban scenario was significantly higher compared to the other scenarios, replicating [20]. Note that sickness may also increase over time, possibly interfering with the observed simulator and scenario effects. The order of presentation was counter-balanced to avoid sequence effects,

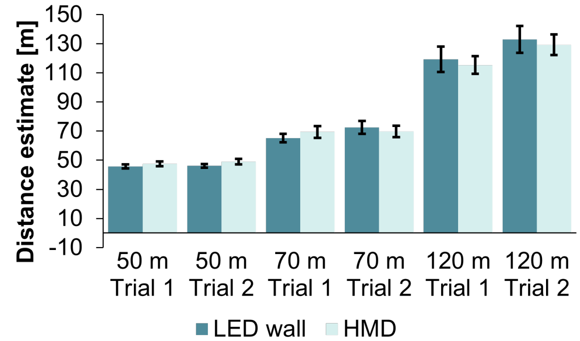

Fig. 6. Descriptive statistics for the egocentric distance perception task.

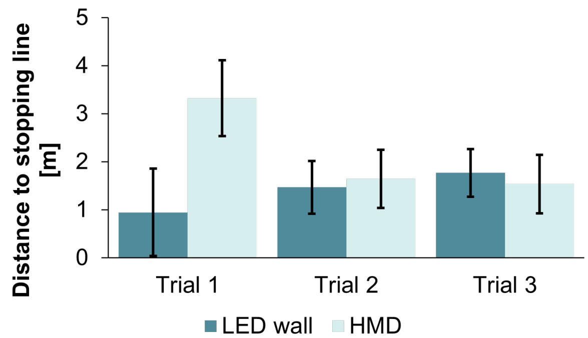

Fig. 7. Descriptive statistics for the target braking task.

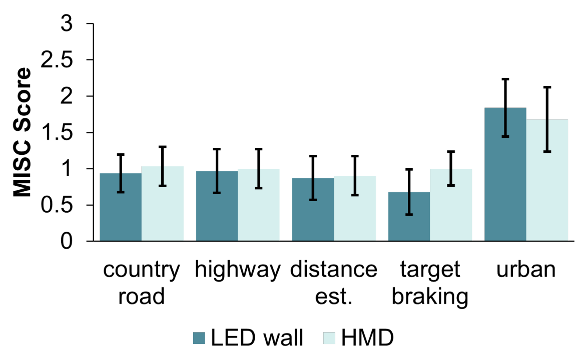

Fig. 8. Descriptive statistics for simulator sickness.

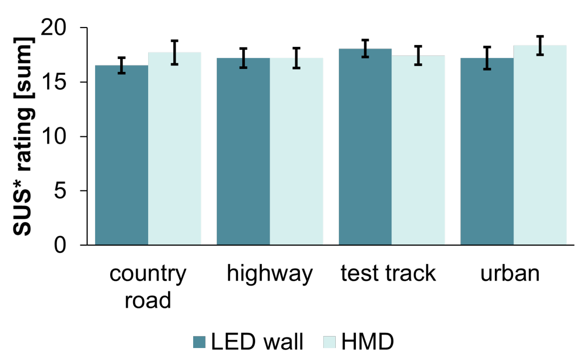

Fig. 9. Descriptive statistics for the sense of presence.

but the risk of carry-over effects remains a weakness of the within-subject design and the sample was comparatively small.

When considering the sense of presence, we found proof of equivalence across the two driving simulators, contradicting our expectations. There were several other studies that likewise did not find any positive effects of HMD use on presence [14], [15]. Furthermore, the present study is the first to compare an HMD against an LED wall. The LED wall technology is considered highly immersive, especially when compared to LCD panels and projection systems. Accordingly, the equivalence across the two simulators could be a result of a particularly high experience of presence in the LED wall simulator. The full vehicle mockup in the LED simulator may have also influenced presence in a positive way [36].

V. Conclusion

The present study was aimed at determining whether HMDs are disadvantageous with regard to application in driving simulators. In fact, on an overall basis, we found neither advantages nor disadvantages to using HMDs. HMDs were found to perform as good as the tested screen-based simulator with regard to simulator sickness and presence, as well as active distance perception. Evidence for passive distance and speed perception was only anecdotal. HMDs may hence provide a cost-efficient alternative for visualization in driving simulation.

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