

# Validation of Hardware for looking around in a VR based Driving Simulation (VALHaLa)

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**Abstract** - Traffic research is crucial due to the high incidence of accidents on roadways, making it essential to understand and improve driving behaviour and safety measures. Utilising simulators provides a safe and controlled environment for studying various driving scenarios. The choice of visualisation hardware in simulator research is a critical factor as it can significantly impact driving behaviour, the occurrence of simulator sickness, and the sense of presence, ultimately affecting the validity of research results. This study investigates how the choice of visualisation hardware influences these subjective and objective criteria. An experimental between-subjects design with 72 participants was employed, featuring three visualisation devices: Triple-Monitor, ViveProEye and Pimax8K-X. The 15-minute driving simulation contained four different environments and 12 everyday driving scenarios. The findings indicate a significant variance in simulator sickness between the visualisation devices. The VR HMD conditions were found to induce significantly higher levels of simulator sickness compared to the Monitor condition. This trend was particularly pronounced in scenarios involving complex driving environments. The results of the study suggest, that while for a majority of scenarios, the choice of visualisation interface might not significantly alter the driving behaviour, specific conditions elicit notable differences, particularly when challenging the drivers' perception and response capabilities.

**Keywords:** Driving simulation, virtual reality, head mounted displays, simulator sickness, presence.

## Introduction

Driving has an everyday relevance for us. Also driving is one of the most complex and dangerous everyday tasks (Allen R.W., 2011). According to the Federal Statistical Office (*Statistischer Bericht - Verkehrsunfälle Zeitreihen - 2013-2022* 2022), around 363,000 road accidents with personal injury were registered in Germany in 2022, of which around 76% involved cars. Simulator research offers a cost-effective and safe way to study various scenarios (Wynne, Beanland and Salmon, 2019). However, to obtain meaningful results in simulation, it is crucial to ensure realistic driving behaviour in Human-in-the-Loop (HuiL) simulations.

Traditional driving simulators have often relied on multiple displays or projections to visualise a virtual environment. Many of these simulators, do not provide a 360° Field-of-View (FoV). The use of Virtual Reality (VR)-Head-Mounted Display (HMD) technology offers the advantages of a high level of immersion by providing a coherent 360° visual experience through stereoscopic displays and head tracking. HMDs also avoid distracting monitor frames within the simulation visualisation and offers the possibility of displaying a complete vehicle interior. Compared to most multi-monitor configurations a HMD approach requires fewer visualisation computers and therefore the overall configuration of the simulator usually becomes more cost effective.

In driving simulation, the visual representation can play an important role in the subjects perception (Utesch, 2014) by improving the feeling of presence.

A definition of presence according to Malone and Brünken, 2021 is: "virtual presence [...] implies that the user feels part of the virtual environment and even has the impression of being spatially present amidst the displayed scenery". Establishing a strong feeling of presence in the simulation is important for the validity of simulation results, particularly with regard to the goal of comparable driving behaviour between simulation and reality (Kemeny and Panerai, 2003). However, the nuanced effects of presence remain subject to ongoing exploration, with outcomes varying based on the contextual variables under investigation (Himmels, et al., 2023). Nonetheless, enhancing presence in driving simulations is widely acknowledged as a positive pursuit, holding promise for advancing the fidelity and applicability of research findings in traffic studies.

Besides presence, an important factor that has repeatedly been observed in other comparison studies was the effect of simulator sickness. The study by (Cao, et al., 2020) provides a good overview of the topic of simulator sickness. According to Cao the most important factors influencing simulator sickness are age, gender, (user related) field of view (HMD related) and simulation duration (study design related) of VR usage. Additionally, Cao mentions, "the amount of virtual motion presented in the game" as another important factor influencing simulator sickness (scenario related).

Driving simulation in the field of traffic research can cause a high degree of virtual motion. In contrast to racing simulations, high driving speed or high lateral

dynamics are less likely the reason for virtual motion. Regular head movements to look around to recognise the surrounding, especially in urban intersection situations in combination with stop and go behaviour caused by the surrounding traffic, creates virtual motion which can increase the occurrence of simulator sickness.

Simulator sickness, the feeling of presence, the driving dynamics as well as speed impression are all influenced by the used visualisation hardware. For VR HMDs in particular, there are various important design-related differences that influence the visual experience. These include, factors as the available FoV (Cao, et al., 2020; Kemeny and Panerai, 2003; Masnadi, et al., n.d.), the Pupillary Distance (PD) (Winkel, Talsma and Happee, 2022), the display technology used (Han and Suk, 2019; Elliott, et al., 2003), the shape of the lenses (Koulieris, et al., 2017) as well as the adaptability of the Interpupillary distance (IPD), Pixels Per Degree (PPD), or the resulting sweet spot (Lee, Hu and Hua, 2016; Kim and Park, 2019). Wearing comfort and increased heat emission, which can lead to dry eyes and headaches, are also relevant factors. Other factors, such as the weight and balance of the HMDs, can further influence the visual perception, the well-being and the reasonable amount of time a participant can spend in a simulation.

With regard to the advantages of VR, a number of studies (Sharples, et al., 2008, Weidner, et al., 2017, Suwarno, Wijayanto and Trapsilawati, 2019, Pai Mangalore, 2019, Malone and Brünken, 2021, Himmels, et al., 2023) have already compared VR technology and traditional visualisation systems like single or multi-monitor, LED wall or projection systems. In the older studies, the Oculus Rift DK1+2 and the VivePro as VR-HMDs were often compared. In the more recent studies (after 2021), more modern HMDs such as the Varjo VR-3 were compared.

It is not yet clear how the driving behaviour as well as the feeling of presence and simulator sickness are influenced by the choice of visualisation hardware. Often times a trade-off needs to be made as certain hardware features may increase the sense of presence, while also promoting simulator sickness. This is exemplified in the comparison between VR vs monitor. It is also unclear whether a more affordable standard VR-HMD is sufficient for traffic research or whether a more advanced, higher-quality VR-HMD with higher resolution and wider FoV, but also higher costs and performance requirements is required. It remains a challenge to find the right balance between cost- and performance efficiency, as well as optimal validity, presence and avoidance of simulator sickness.

## Methodology

The VALidation of Hardware for Looking around (VALHaLa) study aimed to investigate how the choice of visualisation hardware influences subjective and objective criteria, in particular occurrence of simulator sickness (Kennedy, et al., 1993) or, sense level of presence (Schubert, Friedmann and Regenbrecht, 2001), and objective results focusing on user driving behaviour as shown in (Fig.1).

The study utilised an experimental between-subjects

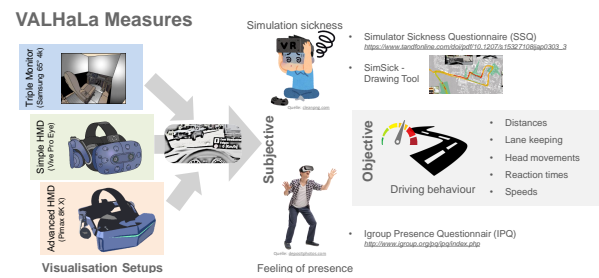


Figure 1: VALHaLa conditions and measures

design to investigate the impact of visual representation in driving simulations on both subjective measures like simulator sickness and presence, as well as objective measures like driving behaviour and distinguishes itself from previous research by directly comparing three setups (Triple-Monitor, VR-simple HMD, VR-advanced HMD) in a consistent simulation environment. It employs a continuous 15-minute driving scenario for deeper immersion, examines 12 standard situations across varied landscapes, and includes a substantial sample of 72 participants. These aspects collectively provide unique insights into the effectiveness of different setups in simulated driving environments, thereby supplementing the findings of previous studies.

## Tested Visualisation Hardware

A simple static simulator with either a triple-monitor or VR-HMD visualisation setup was used to test three different visual representation variants:

1. A triple-monitor setup of the static driving simulator in the MoSAIC laboratory, providing up to 230° FoV. The simulator provides a native 4K resolution for the front screen and a Full HD (1920x1080p) resolution, upscale to 4k for the side screen. The monitors are arranged in a U-shape (Fig.2). Each of the monitors has a 65 Zoll QLED with a 16:9 aspect ratio, 4k(3840x2160p) resolution and a 60 Hz update rate with a reflection reduced design by a minimal surrounding frame operated by a visualisation PC. The simulation environment creates a synchronised multi monitor representation via the unreal 4.27 nDisplay plugin
2. A simple VR-HMD variant (ViveProEye, release date 2019), with a 98° horizontal and 98° verticals FoV and a resolution of 1440x1600p per eye and 90 Hz update rate. As the ProEye was also used in some of the older studies, the results obtained here become more comparable.
3. For the advanced HMD the Pimax8K-X (release date also 2019) was chosen. The Pimax8K-X, with horizontal 159° and vertical 103° FoV and a resolution of 3840x2160p per eye used in a native mode with 90 Hz update rate. In addition to immediate availability, the larger horizontal FoV of the Pimax HMD compared to the Varjo-XR3 was the main reason why the Pimax was used in the study.

In order to keep the performance of the HMD glasses at a high update rate, the simulation did not implement mirrors, which are particularly cost-intensive to render in VR environments. Especially for the monitor users missing mirrors are a significant limitation

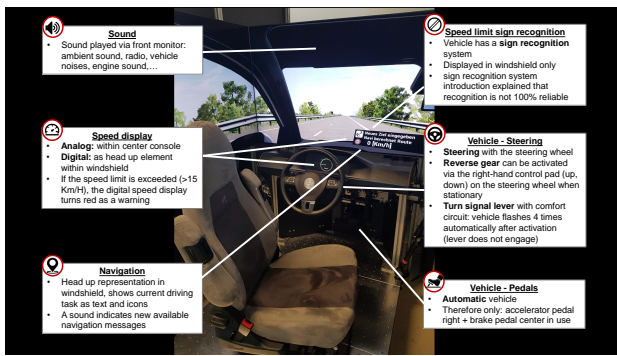


Figure 2: Simulator, simulation setup

of perception. Taking this into account, the study only selected situations in which backward traffic does not exist.

## Simulator

The simulator has a fix base mock-up design (Fig.2). Offering a car seat in front of an active steering wheel. Levers and buttons on the wheel are freely configurable. Within the study, only the indicator lever and the right up/down button on the steering wheel to switch gear between forward and reverse were in use. Two pedals in an automatic gear setup allows accelerating and breaking. An extra instrument display showing the current speed as an analogue value in the mock-up. Three HTC Lighthouse 2.0 base station are available to track VR hardware. In VR condition, the HMD allows a tracking of the test person head. In the Monitor condition, a vive tracker 2.0 fixed with a flexible headband allows also tracking of the test person's head. In VR the hands of the test person were tracked and represented within the simulation to make it easier for VR user to grip the steering wheel. For the hand detection, Manus PrimeX gloves together with two vive Tracker were used. As sound source, the front monitor (stereo) was chosen for all conditions to stay comparable. An instrumental only radio played continuously during the simulation. Vehicle engine, driving and indicator sounds together with further environmental and surrounding traffic sounds were also presented via the front screen speakers.

As visualisation hardware to render the simulation, following (Tab. 1) components were used during the data collection. All render hardware used Windows10 as operating system. Due to a render hardware defect, a switch takes place after Monitor and ProEye and before Pimax data collection:

## Simulation Framework

The simulation was created using Unreal Engine 4.27, with optimisations for VR performance. These included simplifications like no mirrors, static lighting for objects, distance culling, fog effects, and limited draw calls.

In the simulation setup, all visualisation conditions shared several consistent components. The vehicle was represented using a 3D model of a Golf7. The vehicle dynamics were managed by Unreal's

Table 1: Used visualisation render hardware

Condition	Monitor Front and ViveProEye
Processor	AMD Ryzen Threadripper 2950X 3.50 – 4.40
RAM	32 GB DDR4 2666MHz
GPU	Geforce RTX2080 Super 8GB
Condition	Monitor Side
Processor	IntelCore i7 3770 3.4-3.9
RAM	8 GB DDR3 1600 MHz
GPU	Geforce RTX2080Super 8GB
Condition	Pimax8K-X
Processor	IntelCore i9-12900k 3.9-5.1 GHz
RAM	32 GB DDR5
GPU	Geforce RTX4090 25GB

*Wheeled Vehicle Movement Component 4W*, with specific parameters like a mass of 1500kg, a steering wheel rotation up to 900°, a maximum speed of 145 km/h achievable in 19 seconds, an automatic clutch and a tire friction scale factor of 10 to maintain stability. Additionally, AI-controlled traffic moved along spline paths with the initiation tied to Ego-responsive trigger boxes. The system used SteamVR coupled with Unreal LiveLink and the SteamVR API plugin to integrate HMD and trackers. Information regarding navigation, current speed, and speed limits was displayed on a head-up display on the windscreen.

## Environment and Scenarios

In all conditions, participants drove the same route (see Fig. 3) containing several environments (motorway, country road, city, forest path). The aim was to achieve a high level of presence throughout the entire duration of the test. Participants travelled along the route with a distance of approximately 8.7 km, which took them on average 15.35 minutes (SD=1.36 minutes). In order to create a natural driving experience, the real town of Cremlingen and its surrounding area served as the basis for the road layout. Only the forest path is fictional and was supplemented. Along the route, users experienced twelve different everyday driving scenarios:

1. **Construction site**, blocks right lane on an empty highway.
2. **Speed limit**, set a speed limit to 60 km/h for around 300 m.
3. **Highway exit**, with speed limit of 40 km/h.
4. **T-Junction**, with stop sign and crossing traffic.
5. **Slow vehicle**, driving with 25 km/h, while traffic continuously approaches in the opposite lane.
6. **Traffic Light**, within the city of Cremlingen. The traffic light shows a red signal for 30 seconds after stopping at the stop line. Route continuous straight after the traffic light.
7. **Sharp turn**, on a T-intersection with a left-turn greater than 100°
8. **Blocked lane**, blocked by parking cars with a 22 m long gap in the centre of the parking vehicles. Two oncoming vehicles, followed by a third after a short period. A truck is parked at the end of the gap, reducing the visibility of oncoming traffic in the adjacent lane.
9. **Second traffic light**. Route continuous right afterwards.
10. **Second T-Junction**, turning right with stop sign without oncoming traffic.
11. **Sharp curves**, on a narrow forest path with several potholes.

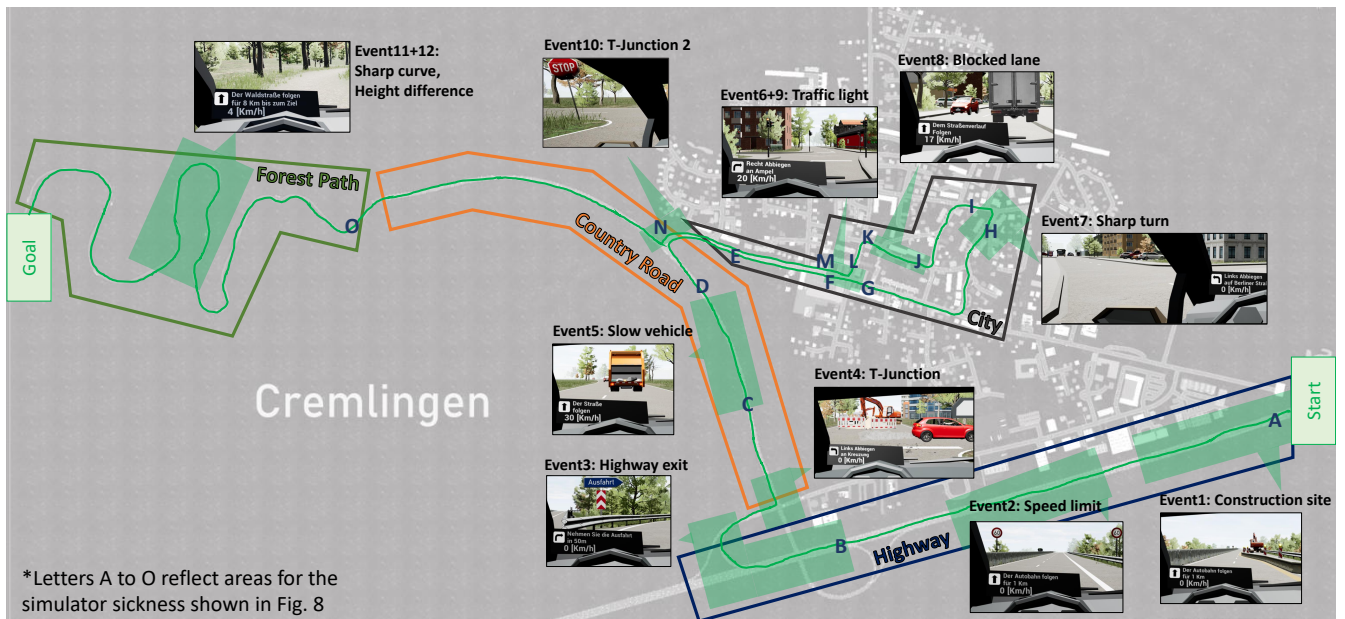


Figure 3: VALHaLa map overview with route, areas and events labelled

12. **Height differences**, on a moderate level in combination with an oncoming vehicle, narrow forest path, potholes and curves.

## Study Details

The final study design was reviewed by an ethics committee and approved on 13 October 2022. A data protection concept regulated the anonymisation of the test participants. The test subjects received €15 per hour. Registration for the study was only possible via the German Aerospace Center (DLR)-Institute of Transportation Systems (TS) participant pool (*DLR-TS Probandenpool 2022*). In order to be eligible for participation the test subjects must be at least 18 years old, in possession of a valid class B driving licence, cannot wear glasses (because of the VR headset) and must not have symptoms of illness at the time of the study.

Seventy-three participants took part in the study (26 female, 37 male). Thirty (9 female) were assigned to the Monitor condition, 31 (10 female) were assigned to ProEye Condition and 12 (7 female) were assigned to the Pimax condition. The average age of the participants was 30.71 (SD= 10.79).

The participants filled out a demographic questionnaire in advance. After a short briefing on the simulator controls and displays they completed a training unit (five scenarios on a route independent of the target environment). Afterwards, the participants were transferred to the starting point of the main test route. In another short briefing the supervisor informed the participants about the start of the video recording and that they would not be disturbed during the ride unless necessary (technical problems, or getting off the route). Participants were reminded they could stop the test anytime if they experienced simulator sickness. After the main route, they completed the Simulator Sickness Questionnaire (SSQ) and used a drawing tool on a 85" touch board to visually indicate

their simulator sickness levels across different route points. Subsequently, they filled out the Igroup Presence Questionnaire (IPQ) and a completion survey.

The study employed a mostly exploratory approach with respect to the influence of the visualisation device on the driving behaviour. Yet, some events were included to analyse specific behaviour in which differences were expected. Regarding the speed limit sign it was expected that participants in the ProEye condition will react later to the speed limit sign, as the resolution of the VR HMD is relatively low. Further, it was hypothesised that participants in both VR conditions, would make more head movements, especially in the city area and at the t-junctions. Additionally, the events slow vehicle, blocked lane and the traffic lights were included to evaluate whether participants in the VR conditions made use of the ability to move their head in order to get a better view (e.g. look around an obstacle).

Based on previous research, it was expected that participants in the Monitor condition will experience the least symptoms of simulator sickness and participants in the Pimax condition will experience most simulator sickness symptoms, due since research has indicated that a larger FoV can lead to simulator sickness. Regarding the sense of presence, we expected a higher sense of presence in the VR conditions than in the Monitor conditions.

## Results and discussion

### Speed

With respect to the average driving speed on the whole run, there is no significant dependency of the visualisation device on the mean driving speed. However, the analysis of single events showed differences in deceleration behaviour.

**Highway Speed Limit:** Differences in driving speed

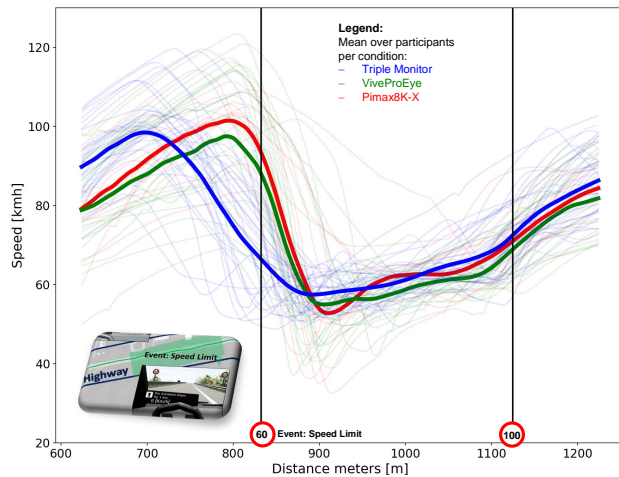


Figure 4: Event: Highway Sign; Driving speed

between the conditions were found for the event speed limit (highway). It can be observed that participants in the Monitor condition reduced their speed earlier in response to the 60 km/h speed limit sign than in either of the VR-HMD conditions (see figure 4). A Kruskal-Willis Test was conducted to compare the mean point in distance where the participants' driving speed dropped below 20 m/s for event speed limit. Results confirmed a significant difference between the Monitor condition and the VR-HMD conditions for speed limit ( $H(2) = 25.71, p < .001$ ).

**Traffic Lights:** Participants in the Monitor condition stopped earlier in reaction to the traffic light than did the participants of the VR HMD conditions ( $H(2) = 24.34, p < .001$ ). This was also confirmed when comparing the distance to the stop line. The mean distance was 4.24 m for the Monitor condition, 2.00 m for the ProEye condition and 2.18 m for the Pimax condition. However, our analysis (using  $-1.5 \text{ m/s}^2$  as a threshold for deceleration) showed that the participants in the Monitor condition did not start decelerating significantly sooner than participants in the VR conditions ( $H(2) = 2.57, p = .276$ ).

Similarly, for the second traffic light, it was found that participants in the Monitor condition stopped earlier at the traffic light, than the VR HMD conditions ( $H(2) = 15.27, p < .001$ ). The difference is however only significant compared to the ProEye condition. These differences were also found in the distance to the stop line. The mean distance for the Monitor condition was 4.00 m, for the ProEye condition it was 1.70 m and for the Pimax condition it was 1.73 m.

**Other:** The evaluation of the driving speed did not reveal any significant differences between the conditions for any other parts of the route.

## Lateral Distance

We evaluated the lateral distance of the participants' trajectories to the right border of the road, in order to examine if there are differences in driving behaviour between the three visualisation conditions.

**Highway Construction Site:** We found differences

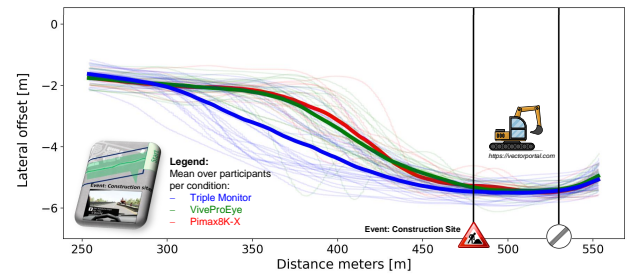


Figure 5: Event: Highway Construction Site; Lane Changing

in the lateral distance for the event highway construction site, which revealed that participants in the Monitor condition switched lanes earlier and in a more gradual angle in response to the construction side, than the participants in the VR HMD conditions (see Fig. 5).

**Slow Vehicle:** Regarding the event country road overtaking we found that the participants in the Monitor condition drove further to the right of the lane behind the garbage truck.

**Other:** For all other events, the analysis revealed no significant differences between the visualisation conditions.

## Head movements - Yaw

With respect to the head movements we expected that more head movements would be made in the VR HMD conditions than in the Monitor condition, since moving the head in VR HMD changes the view into the virtual world, while it does not in the Monitor condition. Further, we expected more head movements in the ProEye than in the Pimax condition, in order to compensate for the smaller FoV of the ProEye headset. Overall, we found a significant difference in yaw head movements between the conditions. As expected, the least head movements were made in the Monitor condition, and most head movements were made in the ProEye condition ( $H(2) = 138.80, p < .001$ ).

**Highway Construction Site:** Our analysis revealed a significant increase in head movement within the ProEye condition compared to the Monitor setup. Specifically, we observed significantly more head turns ( $H(2) = 8.61, p = .01$ ), as well as an increase in the maximum head turn angle, averaged per participant ( $H(2) = 11.12, p = .004$ ). The results suggest that participants in the VR HMD conditions turned their head further than in the Monitor condition.

**T-junction:** For the T-junction event, the quantity of head turns did not significantly differ between conditions. We did however, find significant differences in the average angle of head turns ( $H(2) = 45.51, p < .001$ ). Participants using the ProEye VR headset on average turned their head further, than participants using the Pimax headset. The participants in the Pimax condition in turn, turned their head significantly further than participants in the Monitor condition (see Fig. 6).

**Slow Vehicle:** Regarding the event slow vehicle, a significant difference in the number head movements ( $H(2) = 6.612, p = .037$ ) and the angle of head turns



## Questionnaire Remarks

In the final questionnaire the participants were able to write remarks about the study. These were clustered and compared between conditions. One aspect that was frequently mentioned (11 times), was the absence of rearview mirrors, which participants felt, caused a disruption of the sense of presence. Additionally, nine participants wrote that they would have preferred to have motion in the simulator to make it more realistic, and get a force feedback. Similarly, it was mentioned by participants in the Monitor condition that it was difficult to get a feeling for their own speed (four times in Monitor condition, one time in ProEye condition). Five participants driving in the Monitor setup also stated that the form of visual display negatively affected their sense of presence. Lastly, nine participants in the ProEye condition and four participants in the Pimax condition mentioned that resolution was low, which caused difficulty reading signs.

## Conclusions

In this study, we evaluated the effects of different visualisation devices — Monitor, VR ViveProEye, and VR Pimax8K-X — on driving behavior within a simulated environment. Our primary goal was to analyse in which way the visualisation interfaces influence subjective experiences, such as the sense of presence and the occurrence of simulator sickness, alongside objective, behavioural responses during driving tasks. The findings revealed a complex interplay between the type of visualisation device used and its impact on the participants' driving behaviour, simulator sickness incidence, and their sense of presence within the simulated environment.

Overall, the results of the study suggest, that while for a majority of scenarios, the choice of visualisation interface might not significantly alter the driving behaviour, specific conditions elicit notable differences, particularly when challenging the drivers' perception and response capabilities. Moreover, the study gave us insights into how simulator sickness is related to physical movement of the head and to the quality of the visual experience offered by different devices. We found that these factors can both increase discomfort and make the simulation feel more real.

## Limitations

This study, while providing valuable insights into the effects of visualisation hardware on subjective experiences, objective criteria, and user behaviour in simulator settings, acknowledges certain limitations. First, inaccuracies in tracking head movements in the Monitor condition and hand representations in virtual reality were observed, possibly affecting the data's precision. Additionally, instances where participants got lost (e.g., making wrong turns) led to a loss of immersion and resulted in non-comparable data at crucial intersections. The absence of mirrors in the setup prevented the inclusion of scenarios requiring awareness of rear traffic, such as vehicles approaching from behind, thereby limiting the scope of the driving experience assessed in this study. Microsimulation lags across all conditions, although minor, could not be entirely eliminated, potentially influencing the results. The lack of a motion platform may

have increased the susceptibility to simulator sickness among participants. Lastly, due to a hardware defect in the Pimax condition, the study was limited to only 10 participants, reducing the sample size and potentially affecting the generalisability of the findings. Despite these limitations, our findings contribute to an understanding of the influence of visualisation hardware on driving behaviour in simulator research.

## Speed

The analysis of the driving speed across different events generally showed no differences between the visualisation conditions. However, differences in deceleration behaviour could be observed at specific events. Participants in the Monitor condition reacted earlier to the speed limit sign on the highway, and reduced their speed earlier than participants in the VR HMD conditions. This was not observed at other points, such as at traffic lights or intersections (e.g. the T-junction), where Monitor users did not start to decelerate any sooner than their VR counterparts. This pattern suggests that the monitor likely offered better readability of the speed limit sign, resulting in an earlier response from the drivers. This notion is additionally supported by the remarks in the questionnaire, in which participants who used one of the VR setups repeatedly reported that they had difficulties reading signs, due to the low resolution. It is rather unsurprising the Vive ProEye VR headset, with its lower resolution per eye, struggled with rendering distant objects sharply, particularly affecting the clarity of road signs with text. The lower resolution per eye means that fewer pixels are available, which has a particularly negative effect when objects are further away. However, the Pimax 8K-X, despite its 4K resolution per eye, did not perform as expected in enhancing sign recognition. Due to the wide field of view the high resolution was spread over a larger visual area, and the specific lens and display technology did not sufficiently sharpen distant edges. Thus, users experienced similar difficulties in recognising signs with the Pimax as with the ViveProEye. In contrast, the monitor's native 4K resolution provided clear, sharp visuals, enabling quicker and more accurate recognition of speed limit signs.

Additionally, participants in the Monitor condition stopped further away from the stop line at the traffic lights, yet they did not stop further away from other stop lines at intersections, such as the T-junction. This behaviour might imply an adaptive strategy to ensure an unobstructed view of the traffic lights, which could be obscured by the car's roof in a fixed viewing angle setup like the monitor. Conversely, in the VR HMD conditions, participants had the flexibility to lean forward and look upwards, thereby allowing them to still see the traffic light, even when stopping closer to it. This difference highlights how the physical constraints and capabilities of each visualisation condition can influence driving behaviours, even in seemingly straightforward tasks like stopping at a traffic light.

## Lateral Distance

Differences in driving behaviour with respect to the lateral distance to the right lane marking were only found in a few events. Regarding the highway construction site it was found that participants in the

Monitor condition tended to change lanes earlier and at a more gradual angle compared to other conditions. A possible explanation is, that there was no functioning mirror on the vehicle. Since the participants in the Monitor condition were not able to glance back over their shoulder to check for traffic in the adjacent lanes, they might have opted to switch lanes more cautiously and with a gentler angle, since they lacked the ability to confirm the absence of rearward traffic. This cautious approach underlines how the limitations of the visualisation setup can directly influence driving strategies, especially in situations requiring heightened awareness of one's surroundings. The absence of the rear-view mirror was also mentioned as a limitation in the participants' remarks across all conditions.

An unexpected observation was made regarding the participants in the Monitor condition who drove further to the right of the lane when driving behind a garbage truck. We would have expected that the participants in the Monitor condition would drive further to the left, in order to be able to see past the truck. This lead us to assume that participants in the Monitor condition may have instead kept a greater distance to the truck in order to see oncoming traffic. This was indeed the case, however the difference was not significant.

## Head movements

The analysis of participants' head movements indicates that participants in the VR HMD condition made more head movements and turned their head further than participants in the Monitor condition. In most cases participants in the ProEye condition made the most and the largest head movements. This could be explained by the fact, that the FoV of the Vive Pro Eye smaller is relatively limited, so may have compensated for that. Especially, during scenarios where participants' view was obstructed, such as by a slow vehicle (garbage truck) or parked cars, participants in the VR HMD conditions frequently moved their head to look around the obstacle, indicating participants in the VR HMD condition made use of the fact, that they can move their head in order to shift their viewpoint to enhance their perception of the environment. Interestingly, similar head-moving behaviours were also observed among participants in the Monitor condition (however to a lesser extend), even though it does not influence the view of the simulation. This phenomenon could imply a significant level of immersion within the simulation, to the extent that participants momentarily disregard the fact that they are interacting with a monitor, thereby 'forgetting' the limitations of their visualisation interface.

## Simulator Sickness and Presence

Furthermore, an important aspect of our study was the evaluation of simulator sickness and the sense of presence experienced by the participants across the different visualisation conditions. Our findings indicate a significant variance in simulator sickness between the visualisation devices used. According to the markings in the Drawing tool, the ProEye VR condition was found to induce significantly higher levels of simulator sickness compared to both the Monitor and Pimax VR conditions. This trend was particularly pronounced in scenarios involving complex driving

environments, such as city areas with multiple turns and wooded areas where the road's bumpy nature combined with turns intensified the sensation of discomfort.

The analysis using the SSQ showed slightly different findings, revealing the highest SSQ scores for the participants in the Pimax condition. No significant difference was found between participants in the Pimax condition and in the ProEye condition. However, participants in the Pimax condition reported higher levels of nausea and oculomotor strain than those in the Monitor condition. In general, the correlation between SSQ scores and the drawing tool ratings were high, especially for the nausea subscale of the SSQ, indicating that the drawing tool provided a valid representation of the sensation of simulator sickness.

Further analysis explored the relationship between head movements and simulator sickness, revealing a significant correlation between the frequency of head turns and increased simulator sickness score. This suggests that the physical act of moving one's head to navigate the virtual environment or to compensate for limited fields of view in VR devices might promote the sensation of simulator sickness. However, since the relationship is correlational, the direction of causality remains unclear. It might also be the case, that participants who felt more sick, made less head movements as a consequence.

The results of the IPQ showed no differences with respect to the sense of presence between the visualisation conditions. However, it was indicated by some participants in the questionnaire remarks that the use of the monitor limited their sense of presence.

## Outlook

Future research should investigate the impact of newer VR headsets like the Varjo VR3, known for its superior resolution and distinct technology, on driving simulations. Additionally, integrating rear-view mirrors into the simulation setup is necessary in order to be able to include scenarios involving rearward traffic. This adjustment would enable the simulation to more accurately reflect real-world driving conditions, giving a more complete picture of driving situations, particularly those requiring responses to events occurring outside the immediate FoV. Further enriching simulation scenarios with dynamic traffic elements, including pedestrians, will enhance the realism of the simulated environment.

This study showed that for most standard driving tasks, the three visualisation setups produce similar results in driving behaviour. Notable differences occurred however, with respect to the perception of visual stimuli, such as the ability to read signs from distance or the ability look past object through head movements. There were no significant differences in presence between the visualisations, but higher values for simulation sickness under the VR HMD conditions. In addition, some participants in the Monitor setting indicated that the form of visualisation negatively affected their sense of presence. These results could indicate a need for further research regarding an appropriate measure for the sense of presence, since the open questions and the results of the IPQ contradict each other.

## Used Acronyms

<b>DLR</b>	German Aerospace Center
<b>HMD</b>	Head-Mounted Display
<b>TS</b>	Institute of Transportation Systems
<b>HuIL</b>	Human-in-the-Loop
<b>VALHaLa</b>	VALidation of Hardware for Looking around
<b>VR</b>	Virtual Reality
<b>FoV</b>	Field-of-View
<b>SSQ</b>	Simulator Sickness Questionnaire
<b>IPQ</b>	Igroupe Presence Questionnaire
<b>IPD</b>	Interpupillary distance
<b>PPD</b>	Pixels Per Degree
<b>PD</b>	Pupillary Distance

## Author contributions

**Gerald Temme:** Conceptualization, Writing - Original Draft, Data analysis, Implementation: Software, Hardware. **Melina Bergen:** Writing – Original Draft, Data analysis. **Eric Nicolay:** Data analysis. **Kilian Gröne:** Implementation, Software, Hardware. **Michaela Rehm:** Implementation, Software. **Martin Fischer:** Supervision, Writing - Review and Editing, Funding acquisition.

## Acknowledgments

The authors would like to thank the Human Centered Simulation group and Research Infrastructure Management of the DLR TS for their continuous support to build up and maintain the MoSAIC-VRU research facility and simulation tool chain. The reported work was conducted based on funding provided by the Helmholtz community.

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