Queasy Rider: How Head Movements Influence Motion Sickness in Passenger Use of Head-Mounted Displays

Jingyi Li
LMU Munich
Munich, Germany
jingyi.li@ifi.lmu.de

Agnes Reda
LMU Munich
Munich, Germany
agnes.reda@campus.lmu.de

Andreas Butz
LMU Munich
Munich, Germany
andreas.butz@ifi.lmu.de

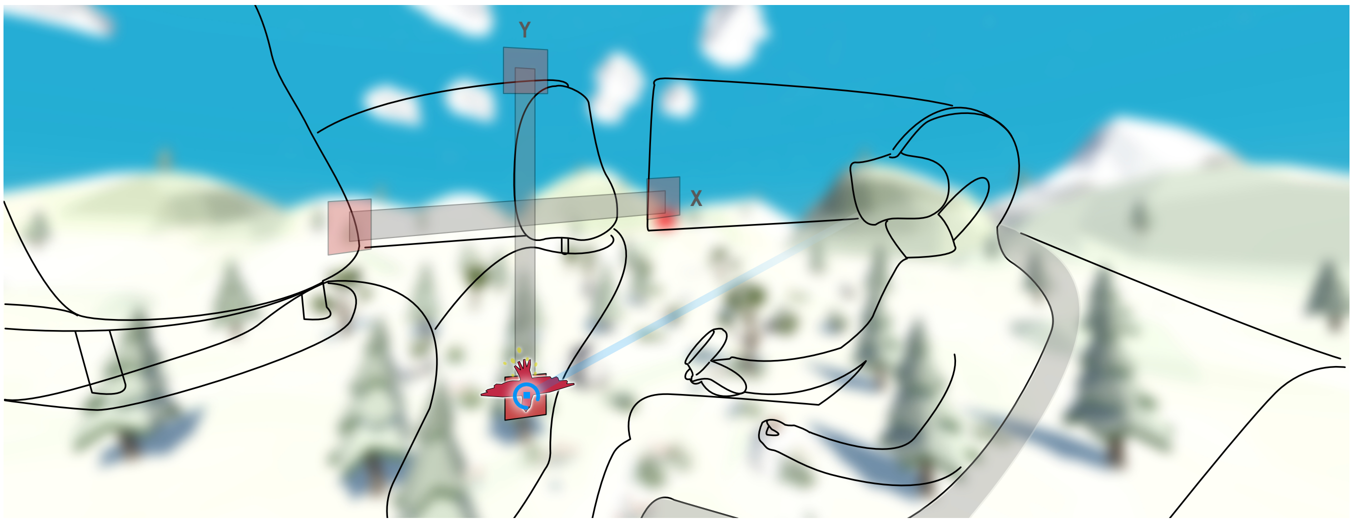

Figure 1: Passenger using a Head-Mounted Display for head-gaze-based interaction around the pitch (Y) and yaw (X) axis.

ABSTRACT

In autonomous cars, drivers will spend more time on non-driving-related activities. Getting their hands off the wheel and eyes off the road, the driver, similar to a rear-seat passenger today, can use multiple built-in displays for such activities or even mobile head-mounted displays (HMDs) in virtual reality (VR). A wider motion range is known to increase engagement, but might also amplify the risk of motion sickness while switching between displays. In a rear-seat VR field study (N=21) on a city highway, we found a head movement range of ±50° with a speed of 1.95m/s to provide the best trade-off between motion sickness and engagement. Compared to the pitch (Y) axis, movement around the yaw (X) axis induced less discomfort and more engagement with less motion sickness. Our work provides a concrete starting point for future research on self-driving carsickness, starting from today's rear-seat passengers.

CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Field studies**; *Virtual reality*.

KEYWORDS

motion sickness, engagement, rear-seat passenger, head movement, head-mounted display

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1 INTRODUCTION

Motion sickness occurs in different transportation contexts in the form of train sickness, seasickness, or airsickness. In aviation, the visual display of a 3D artificial Earth-fixed pattern was found to mitigate airsickness and enhance comfort [16]. In their everyday trips on roads, passengers lack such integrated display solutions and spontaneously seek workarounds such as medication (travel sickness pills), pausing problematic activities (e.g., reading), or looking out of the window. These measures fight the cause of motion sickness, which, according to the widely accepted sensory conflict theory, is incongruent information received by human vision and

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vestibular systems [49]. Passengers suffer more from carsickness than drivers in today's cars. This is attributed to the lack of control in driving and the resulting difficulty to predict future motion [50]. When we expect that an autonomous system will do the driving, we also have to anticipate more drivers assuming the new role of passengers, thereby also missing such anticipatory cues and suffering from self-driving carsickness [13, 14]. Prior research on non-driving-related activities (NDRAs) underlines the potential for the driver to spend more time on work and well-being in upcoming autonomous vehicles [31, 54]. To support a wide range of NDRAs during the journey, modern cars are actively adopting technologies ranging from interactive large displays integrated into current models (e.g., Byton's 48-inch screen [8]) to future concepts using see-through displays (e.g., Nissan's Invisible-to-Visible in augmented reality [43]) and head-mounted displays (HMDs, e.g., Audi's Holoride in VR [24]). Switching between these displays involves frequent and voluntary head movements, which enhances the feeling of engagement in (potentially multiple) activities but amplifies motion sickness simultaneously.

In a passenger VR field study, Paredes et al. [45] found that an increased range of head movement fosters engagement with the virtual world but induces motion sickness as well. Therefore, they highlighted the need to determine an optimal level of head movement by defining an upper threshold of "over-engagement". It is unknown whether a lower level of guided head movements could be embedded as an interaction method to increase user interaction and enjoyment while simultaneously decreasing the risk of motion sickness. We hence explore the upper threshold for range, speed, and orientation of passenger head movements (using HMDs) to create an engaging experience while limiting motion sickness. Unlike prior work that mainly explored mitigation strategies in virtual environments (e.g., peripheral visual motion cues [23, 39]), we aim to better understand the influence of such movements. Our goal is to quantify optimal head movements (regarding range, speed, orientation, and dwell-time) for a good trade-off between motion-sickness and the feeling of engagement in their activities.

To this end, we conducted a rear-seat VR field study, in which 21 participants wearing an HMD were riding in the rear seat on a city highway. They performed head-gaze-based interaction tasks (cross shooting targets) in a virtual environment, while their HMD precluded a view of the real surroundings.

2 RELATED WORK

2.1 Reasons for Motion Sickness

Motion sickness is mainly caused by the conflicts between the motion information received by the human's vestibular and visual system [49]. The umbrella term motion sickness consists of physically induced forms like carsickness, seasickness, and airsickness, and visually induced forms (or visually induced motion sickness, VIMS) like cinema sickness (large image format like IMAX), cybersickness, and simulator sickness [14]. Carsickness, for example, occurs when a passenger is reading books (for a while) in a moving car, as the information received by the visual sensor receptors (i.e., static text printed on the paper or displayed on an e-reader) is contradictory to the one from the vestibular system (i.e., movements of the car). In contrast, cybersickness occurs due to the mismatch between the stationary vestibular information (i.e., a seated participant in a lab study) and the fast-moving content on the simulator display (i.e., car racing on winding roads simulated in a 360° virtual environment). While carsickness is mainly associated with horizontal accelerations caused by accelerating, braking, and cornering [18, 67, 68], it also depends on the motion profiles of car models (compact vs. sport), road conditions (paved vs. unpaved), traffic environments (stop-and-go on urban streets vs. constant speed on a city highway), and driving style (cautious vs. aggressive) [13]. Faced with carsickness, a large body of automotive research explored mitigation strategies for the front driver and co-pilot, for example by the positioning of in-vehicle displays [30] or scent [53], as well as for rear passengers via the active lateral head-tilt strategy while relaxing [69], space-stable imagery on in-vehicle displays [26, 27], or additional visual cues displayed under or next to the text user interface (UI) while reading on the way [20, 41, 42].

2.2 Driver vs. Passenger Carsickness

Compared to the driver, rear passengers suffer from more severe carsickness due to the lack of control over driving and consequently missing anticipatory information [50, 62]. In anticipation of the new role of passengers in autonomous vehicles, Diels and Bos coined the term *self-driving carsickness* [13]. Given the rise of display technology and the increased adoption by the automotive industry, rear passengers will likely perform their desired activities on multiple, large displays. However, watching such in-car displays is known to increase carsickness [26, 27]. The extreme case of large, multiple displays integrated or brought in to the car [13] could be that even side windows are replaced with large displays, thus creating a dense virtual layer of simulated display(s) and information overlaid on the physical car interior [43], or a Holoride, i.e., a full escape from the real world by using VR HMDs [24]. In this work, we focus on the use of VR HMDs by rear passengers and its impacts on their motion sickness, thereby anticipating future head-worn see-through displays like augmented reality glasses. Compared to current physical displays, the choice of a VR HMD represents the worst case, namely a superposition of carsickness and VIMS/simulator sickness.

2.3 Passenger Activities and HMD Usage

The rapid developments in autonomous driving have triggered research on NDRAs in which a driver can spend the time saved from driving on other desired activities such as work or well-being [31, 54]. The activities requested by today's car users imply a rather passive passenger state: They intend to use most of the time for, e.g., looking out of the window at the surrounding traffic and landscape, watching videos on an integrated in-car tablet, using the phone for multiple activities, or listening to music [12, 22, 46]. To support the use of multimedia applications, HMD technology such as VR headsets, was applied in different passenger contexts ranging from in-flight usage [71], public road transport [56, 59], to in-car applications for passenger productivity [33, 33], entertainment [19, 23, 24, 29, 32], and even meditation [45]. Meanwhile, research on the passenger use of HMDs investigates multiple challenges [9]. McGill et al. [37, 40] highlighted the three major challenges for deploying HMDs in the passenger context: social acceptability, confined space, and most predominantly motion sickness.

Mitigation strategies for motion sickness, similar to the ones for passenger use of car-mounted tablets or lap-held notebooks [20, 41, 42], were found effective with the design of visual motion cues synchronised to the motion of the car in the peripheral vision [39]. Moreover, Cho and Kim showed the potential of using a VR HMD to mitigate front-seat passenger carsickness by aligning virtual content to the motion of the car [11]. However, in a calming VR study for the front-seat passenger, Parades et al. [45] found that the HMD users attempt to move around their heads with a less controlled trajectory and an increased range while viewing the 360° virtual content. The observed head movements enhanced their feeling of engagement in the VR viewing activity with limited attention or focus guidance while inducing severe motion sickness [45]. Similarly, in a mobile productivity scenario, HMDs could benefit from a flexible number of virtual displays or UIs replicating a familiar real workspace with multiple displays or beyond [33, 38]. However, the resulting head movement associated with the arrangement of virtual displays might increase passenger motion sickness.

2.4 Head-Gaze-Based Interaction in VR

Common input schemes for VR include hand-held controllers and gaze pointing gestures, as well as their combination. In comparison to hand-held controllers, head-gaze-based interaction is a possible solution to the problem of confined space in vehicles since it requires less space. However, compared to controllers, head-gaze interaction triggered reports of nausea in a navigation task [2]. A dwell-time-based approach could address this issue by extending the time that the user keep the head gaze at the UI to trigger an action and the interval between two successive head gazes. In prior work, users found dwell-time-based interaction non-intuitive, as they have to wait a bit to trigger an event [64]. However, dwell-time-based UIs can work for simple tasks in mobile scenarios, because dwell-time is an adjustable and controllable factor for head movements. Stampe et al. [61] recommend different dwell-times, depending on the difficulty of a cognitive task. A dwell-time of 700 ms or less is suited for simple tasks, whereas $1s$ is suggested for more difficult tasks. Some studies preferred the value of $1s$ to trigger actions in a game environment [2] or sort out a puzzle via gaze [4]. For easy tasks, e.g., keyboard selection, a dwell-time of 500 *ms* or lower has been chosen [21, 48]. Thus, we chose a dwell-time of $1s$, as well as a shorter ($0.3s$) and a longer ($3s$) one.

For head movement, Tanaka et al. [66] found a trade-off between presence and sickness at an optimal visual angle of ±75°. The range is close to the field of view (FoV) of both human eyes which ranges from -80° to 80° [1]. In order to detect interaction and events, it is advised to place visual interfaces and events within this range of eyesight. Otherwise, the user has to search the environment for the next event trigger, which provokes unnecessary head movements and affects motion sickness. In general, the user's FoV consists of four areas: central (0° to 18°), near-peripheral (18° to 30°), mid-peripheral (30° to 60°) and far-peripheral vision (60° to 100°) [36]. Considering the orientation of head movements, Saito et al. [52] examined head movement interfaces regarding their effectiveness, user experience, realistic motion and motion sickness. In a VR driving simulation, the user study participants steered a vehicle by moving their heads along three different axes: the yaw (X), the pitch (Y) and the roll (Z) axis. It was discovered, that motion sickness didn't occur during pitch and yaw head movements in the stationary lab setup [52]. Applying and transferring the results to a field study, we decided to examine only head movements around the pitch and the yaw axis.

3 REAR-SEAT VR FIELD STUDY

3.1 Study Design, Conditions and Protocol

We based our setup on a motion frequency of $0.2\ Hz$ (elicitation of VIMS) [15, 53, 55] and designed the following variants of head movement tasks (see Table 1): i) three *ranges* with their calculated *speeds*, ±25° with $0.76 m/s$, ±50° with $1.95 m/s$, and ±65° with $3.52 m/s$; ii) two *orientations*, pitch (Y) axis and yaw (X) axis; and iii) three *dwell-time durations*: short ($0.3s$), middle ($1s$), and long ($3s$). To elicit motion sickness and, more importantly, prevent participants from severe discomfort, we strictly removed some with a higher susceptibility to motion sickness. The study setup and procedure were approved by the local ethics review board of LMU Munich (ID: EK-MIS-2021-046). We used a within-subject design. Overall, there was one trial round and three conditions (A, B, C) with four different head movement ranges (0°, ±25°, ±50°, ±65°), in which users had to perform head-gazed-based interaction for four (in trial) or eight rounds (in conditions) per dwell-time duration ($0.3s$, $1s$, $3s$). The procedure always started with a trial, followed by the three conditions in a randomised order. In each condition, each pair of head range and dwell time (e.g., ±0.3X) also appears in a randomised order.

Table 1: $3*6$ factorial design with the range conditions (with speed) and the dwell-time (with axis). The speed is calculated from the head rotation frequency of 0.2 Hz, the respective motion range in the condition and the target distance.

f = 0.2 Hz	0.3X	1X	3X	0.3Y	1Y	3Y
A (±25°, 0.76 m/s)						
B (±50°, 1.95 m/s)						
C (±65°, 3.52 m/s)						

3.2 Study VR Environment

To immerse the passenger in a rear-seat VR activity, we designed a snow-covered low-poly landscape background consisting of dynamic natural elements like terrains, trees, grass, plants, moving clouds, falling snow, and jumping squirrels. To integrate the head-gaze-based task into the virtual environment, we added a red guiding bird that moves horizontally or vertically to the red targets at the same speed as the progress bar. When the passenger's head gaze hits the bird, sparkles will appear around the bird to motivate users to stay consistent with their head movement speed. Moreover, when a red target is hit, it will disappear with a small burst effect. We additionally added sound effects when a target is hit and nature background sounds such as birds singing and wind chimes. In analogy to reading a book in the rear seat, we intentionally omitted visual motion cues and a moving virtual environment synchronised to the car movements which was found influential on motion sickness in a prior rear-seat VR study [39]. The entire VR prototype was built in the Unity 3D game engine (version 2019.3.15f1).

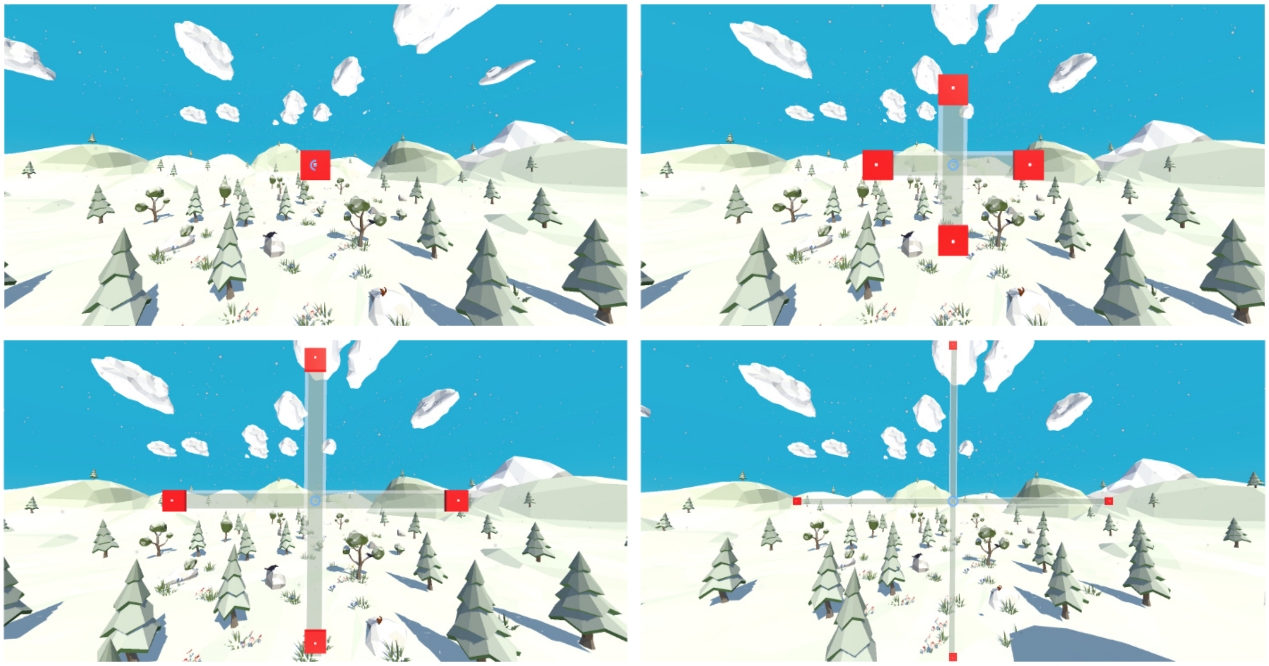

Figure 2: The trial round and three conditions in clockwise order from the top-left: trial round 0°, training on the three dwell-time durations; condition A ±25°; condition B ±50°; condition C ±60°. The three conditions are a demonstration of all four targets, while the testing scene in the study only shows one axis at a time.

3.3 Study Task

For each range of head movement, we implemented four red targets in two pairs (left-right, top-bottom) on the pitch and yaw axis, respectively (see Figure 2). To examine motion sickness on all areas of the FoV, we designed the range of ±25° (A) for near peripheral vision, ±50° (B) for mid-peripheral vision, and ±65° (C) for far-peripheral vision [36]. Below, we refer to these three ranges as condition A, B, and C. In condition C, we originally implemented the range from ±75° for equal intervals across conditions. However, in a testing round the experimenters seated in the car rear seat were unable to reach the target at 75° without involving the whole body. We thus scaled down the range to ±65°, but stayed within the far-peripheral area [36].

Another potentially relevant factor is the speed of the passenger head movements when moving between each pair of targets. Based on the frequency of 0.2 Hz tested in prior work [15, 53, 55], we implemented a cross-like two-dimensional progress bar connecting the two targets in each pair to control the frequency of head movements. The progress bar moves at a speed that matches 0.2 Hz which means the participant should complete each condition in 5 s. Thus, the reaction time is 2.5 s for a pair of targets and 1.25 s from the user's centre anchor point (0°) to a target. Thus, movement speed of the viewed position is different across conditions (A: $0.76m/s$; B:$1.95m/s$; C: $3.52m/s$). The targets were designed according to three key considerations [13]: i) Size: Each target is a red square of $27.4 * 27.4cm$; ii) Position: The four targets are 0.96 m away from the centre along the X- and Y-axis in condition A, 2.44 m in B, and 4.40 m in C. All the twelve targets were on the same plane with a distance of 2.05 m away from the position of the main camera; iii) Content: each target included an identically sized hover area. Additionally, we added a white point in the square centre. When users aim their gaze at the white point in the square target, it snaps to the respective angle for the condition. We provided a blue pointer as a visual feedback for the participant's head gaze, which turns into a circular progress bar when the head gaze is kept at the hover area for a certain duration. As soon as the circular progress bar is completed, the red target changes its position.

3.4 Measurements

To measure the influence of head movements on motion sickness and the feeling of engagement, we used physiological measurements of ECG [10, 47, 53, 60, 65] and subjective reports of Simulator Sickness Questionnaire (SSQ [28]) for motion sickness. For ECG data recording, we used the Polar Band H10 Heart Rate Sensor [17], connected via Bluetooth to Elite HRV, a phone application. For SSQ, we asked our participants to fill out the questionnaire by rating their feelings of sickness during the VR experience on the way. It provides precise measurements for Heartrate (HR) and RR Intervals, from which we derived several additional measurements, such as the root mean square of successive RR interval differences (RMSSD) and the square root of the Baevsky's Stress Index (SI) [3]. To capture the engagement in the head-gazed-based VR task, we measured presence using the igroup presence questionnaire (IPQ [58]), user experience using the user experience questionnaire-short (UEQ-S [57]) with an additional item on concentration [45] ("Distracted from VR by the real world" = 1 to

7 = "Concentrated in VR"). Finally, we asked questions after each condition was experienced and conducted a semi-structured interview at the end to acquire subjective comments and ratings of comfort, engagement, and motion sickness. Participants were asked to report a numeric rating based on a scale from 1 to 7 with 1 indicating "completely uncomfortable/disengaging/non-motion-sick" and 7 for "completely comfortable/engaging/motion-sick".

3.5 Field Setup and Test Route

We used the Oculus Quest [44], a consumer-grade standalone VR headset with 6-DoF inside-out tracking, a 2880×1600 twin OLED display, 72 Hz refresh rate, a FoV of 94° horizontal and 90° vertical (130° diagonal), and two 6-DoF hand-held controllers. The HMD also provides a fully integrated open ear headphone with spatial audio. We tracked passenger head movements via the VR headset which was connected via USB to a laptop (MacBook Air 2012). We mapped the left-hand controller to the real-time car movements and synchronously subtracted it from the rotation of the VR Headset. The controller was fixed on the right side door next to the rear passenger seat. We chose a 4.4 km city highway with relatively controlled traffic conditions, a good road quality and a constant driving speed. The main test route was an almost straight road with a slight curve for about 5 minutes of driving. Throughout the study on the highway, the experimenter controlled the driving style with a constant speed of 80 km/h (following the indications from the mobile navigation) in a Toyota Yaris Hybrid and performed no stops in between. The trial round was executed in a stationary vehicle at the beginning before entering the highway.

3.6 Participants

We recruited 21 participants from personal contacts of locals. We pre-screened our participants and excluded those with a higher susceptibility to motion sickness based on the Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-S [7]). In total, we excluded three participants who had a MSSQ raw score higher than 30.4, the 95% percentile [7]. This precaution is necessary for motion sickness studies [53] and particularly essential in this field study where the participants were exposed to an actual risk. Enrolled participants were 12 men and 9 women aged from 16 to 60 years (M = 27.4, SD = 12.1) with a mean MSSQ raw score of 12.6 (SD = 7.44). Most of them (n=17) had no or rare prior VR experience. The most commonly used VR headset was Oculus (n=5). Before the global pandemic, all participants travelled regularly as a passenger in cars ranging from monthly (n=6), weekly (n=12), to daily (n=3). Their most frequent trip length was 30 minutes to one hour (n=10).

3.7 Procedure

Before the field study on-site, we sent participants an invitation with a MSSQ-S questionnaire link, study information and a consent form. Based on the MSSQ results, we sent the qualified participants their date, time slot, location, and dress code instructions for placing the heart rate band. We also asked them to avoid food consumption an hour prior to the study [72]. Besides, they were asked to not be under the influence of alcohol or medication. Throughout the study, the participants could pause or terminate the study when they experienced any motion sickness symptoms. In front of the car on-site, the experimenter welcomed the participant. Both disinfected their hands and kept wearing masks throughout the study. Next, the experimenter got into the driver's seat, and the participant was seated on the rear seat, diagonally behind the driver. In the car, the participants were introduced to our hygiene concept and study procedure, followed by a demographic questionnaire asking about their prior VR and passenger experience. The experimenter instructed the participant to put on the ECG respiratory band to record the baseline data for 5 minutes.

Before putting on the HMD, participants were introduced to its usage (particularly with a facial mask) and to the head-gaze-based task in VR. In a 5-min trial round while the car was parked, they were asked to wear the HMD and familiarise themselves with the dwell-time-based interface by hitting targets in their central view (0°). When triggered, the red target disappeared for five seconds. In between, participants could view the virtual environment freely. They experienced three dwell-time durations, each pair appearing four times in a randomised order. When the trial was over, the participants saw a display showing a Break button, and they had to take off the HMD.

After checking seat belts, the experimenter drove the participant towards the city highway. Upon instruction by the experimenter when performing the pre-defined constant speed, the participant put on the HMD again and continued the next condition by keeping their head gaze on the Break button for five seconds to trigger the scene. In the condition, each participant perform the head-gaze-based task by hitting the targets along the X- and Y-axis with their head movements. They experienced three dwell-time durations with each pair appearing eight times in a randomised order. Similarly, the participant ended a condition and took off the HMD when they saw the Break button. During this break, the experimenter exited the highway and parked the car, so that the ECG data could be recorded in a stationary environment. Meanwhile, the participants filled out the questionnaires. The procedure was repeated for the remaining conditions. After this, the experimenter conducted a semi-structured interview (with audio recorded) asking about the overall rear-seat VR experience, reactions, and opinions regarding the experienced head movement ranges, speeds, orientation, and dwell-time durations. The entire study took about 100 minutes. Each participant was compensated with 10€.

4 ANALYSIS AND RESULTS

To evaluate the influence of head movements on motion sickness and engagement, we analysed the quantitative data from the physiological measurements and the questionnaires, as well as the qualitative data from the semi-structured interview. For statistical analysis, we used a one-way repeated measures ANOVA (RMANOVA) in JASP [25] to examine whether there is a significant difference in dependent variables across three conditions. Statistical significance is reported for $p \leq .05$. A large effect size is reported if it is > 0.5.

4.1 Performance

We tracked our participants' head movements in each condition with Unity. The descriptive statistics are shown in Table 2. None of our participants reported any observable latency while performing the tasks. Overall, our participants managed to hit all pre-programmed targets in all conditions. However, their exact performance, i.e., the range and speed of their head movements, differs between conditions.

Table 2: Descriptive statistics of the mean (*M*) range and speed of rear-seat passenger head movements, standard deviation (*SD*) in brackets, and the deviation (*D*) from the pre-programmed standards.

Condition (0.2 *Hz*, 2.5 *s*)	A (±25°, 0.76m/s)	B (±50°, 1.95m/s)	C (±65°, 3.52m/s)
Time (*s*): *M*	2.26 (0.41)	2.56 (0.30)	3.14 (0.92)
Time (*s*): *D*	-0.24	+0.06	+0.64
Speed (m/s): *M*	0.85 (0.11)	1.91 (0.21)	2.80 (0.66)
Speed (m/s): *D*	+0.09	-0.04	-0.72
Range (°): X	25.02 (0.55)	49.48 (0.95)	64.36 (0.68)
Range (°): Y	24.74 (0.61)	49.14 (0.96)	63.94 (0.57)
Range (°): *D* X/Y	+0.02/ -0.26	-0.52/ -0.86	-0.64/ -1.06

While performing the tasks in the HMD, participants accelerated their head movements as the range widened. They were on average 0.24 *s* and 0.09m/s faster in condition A but 0.64s and 0.72m/s slower in condition C. In comparison, they completed the task with a minimum deviation of 0.06 *s* and 0.04m/s in condition B while moving ±50° along the yaw (X) and pitch (Y) axis. Still, this deceleration in condition B also reflected in the narrowed range of head movements on average by 0.52° on the X-axis and by 0.86° on the Y-axis. Similarly, in the wider condition C, participants voluntarily narrowed their head movements along the Y-axis (by 1.06°) more than the X-axis (by 0.64°). While in condition A, participants widened the range by 0.02° horizontally but narrowed by 0.26° vertically on the Y-axis. Consistent with the wider horizontal FoV in human visual perception [36], the user head movement along the X-axis was wider than along the Y-axis. Taken together, participants performed best in condition B (±50°), with the least deviation in the calculated time and speed. However, their voluntary movements imply a demanded range smaller than ±25° on the pitch axis and ±25° to ±50° on the yaw axis.

4.2 Motion Sickness

Overall, none of our participants reported heavy motion sickness symptoms throughout the field study, despite occasional feelings of discomfort after performing the head-gaze-based task in each condition using the HMD. Table 3 shows the descriptive statistics of our ECG data measured while the car was parked at the beginning of the study (baseline) and after each condition (A, B, C).

A RMANOVA revealed significant differences in Heart Rate Variability (HRV): the RMSSD, F (1.02, 19.5) = 12.1, p <.05, ω^2 = 0.26 and the Stress Index (SI) [3], F (1.64, 31.1) = 10.9, p <.001, ω^2 = 0.15. Post hoc testing using a Bonferroni correction revealed that RMSSD decreased significantly after the participants put on the HMD, Baseline (BL) − A (mean difference = 222 *ms*, p <.05), BL − B (mean

Table 3: Descriptive statistics of the ECG data with the means (*M*) and the standard deviation (*SD*) in brackets.

Condition	Baseline	A (±25°)	B (±50°)	C (±65°)
HR (bpm)	73.14 (11.26)	70.52 (8.00)	71.20 (10.72)	71.19 (9.25)
RR (ms)	840.62 (134.96)	861.57 (101.71)	861.95 (129.73)	857.81 (115.39)
RMSSD (ms)	286.23 (283.07)	63.16 (46.38)	64.93 (46.27)	65.56 (54.19)
LF/HF (ratio)	2.78 (1.08)	2.70 (2.02)	3.16 (3.35)	2.61 (2.19)
SI (index)	5.1 (3.62)	8.52 (2.86)	8.14 (2.79)	8.51 (2.48)

difference = 222 *ms*, p <.05), and BL − C (mean difference = 218 *ms*, p <.05). SI increased significantly as well, BL − A (mean difference = -3.21, p <.05), BL − B (mean difference = -2.93, p <.05), and BL − C (mean difference = -3.07, p <.05). High values of the SI and low values of the RMSSD in Condition A shows a highest activation of the sympathetic nervous system (SNS) activity which signalises mental stress and motion sickness [3, 60]. Nonetheless, the differences between the condition A, B, and C for RMSSD and SI are small and not statistically significant. In comparison, participant's self-reported symptoms of motion sickness based on the Simulator Sickness Questionnaire (SSQ) revealed differences across the three conditions. Stanney et al. [63] examined that SSQ scores higher than 20 are indicating concerning motion sickness symptoms. All three calculated means for the total score of the three ranges are above this proposed threshold value. As shown in Table 4, participants reported more severe motion sickness with a higher total score (TS) in a wider range of head movements. However, a RMANOVA test found no significance with F (2, 40) = 1.353, p = .27, ω^2 = 0.006. We further analysed the sum scores of each category (Nausea, Oculomotor, and Disorientation) and found no significant differences across conditions.

Table 4: Descriptive statistics of Simulator Sickness Questionnaire weighted sum scores with means (*M*) and the standard deviation (*SD*) in brackets: Nausea (N), *9.54, Oculomotor (O), *7.58, Disorientation (D), *13.92, Total Score (TS), *3.74 [70].

Condition	A (25 °)	B (50 °)	C (65 °)
TS	27.35 (36.12)	34.37 (30.09)	40.08 (35.86)
N	20.90 (23.11)	29.98 (21.89)	30.44 (23.11)
O	19.49 (30.46)	21.64 (21.97)	28.88 (31.09)
D	34.47 (52.37)	41.10 (47.15)	51.70 (49.57)

4.3 Engagement

We evaluated the participant's feeling of engagement in the task through their presence (IPQ) and user experience (UEQ-S) with an additional item about concentration [45] in the virtual environment. In addition, we asked questions after each condition to acquire subjective ratings of comfort, engagement, and motion sickness, which we refer to as Range Rating. After each condition,

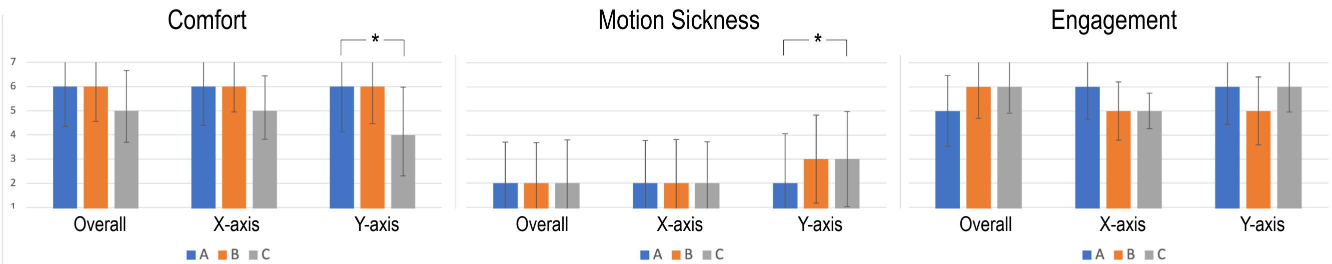

Figure 3: Range Rating results of comfort, motion sickness, and engagement on the overall experience, X-axis, and Y-axis. * indicates a significant difference between two conditions with $p \leq 0.05$.

participants rated their head-gaze-based interaction on a 1-7 Likert Scale, and one participant's invalid entry was excluded. Overall, they reported a moderately to highly comfortable and engaging rear-seat VR experience with a low level of motion sickness across conditions and orientations of head movements (see Figure 3). Participants found their head movements along the Y-axis overall less comfortable (MD = 4, SD = 2.03) in condition C, where they also felt more motion sick (MD = 3, SD = 1.98) in comparison to condition A. RMANOVA tests showed significant differences in the participant's reports of comfort, F (2, 38) = 6.27, p <.05, ω^2 = 0.096, and motion sickness, F (2, 38) = 6.18, p <.05, ω^2 = 0.043. Post hoc tests using the Bonferroni correction revealed that our participants' comfort decreased significantly after moving their heads broader from 50° to 130° vertically, condition A - condition C (mean difference = 0.667, p <.05), and their motion sickness increased significantly (mean difference = -1.10, p <.05). However, we found no significant difference between condition B and A or C along the Y-axis regarding comfort and motion sickness. With regards to engagement, we found contradictory results especially in condition A, where our participants rated their overall experiences (MD = 5.0, SD = 1.47) lower than the ones on the X- (MD = 6.0, SD = 1.33) and Y-axis (MD = 6.0, SD = 1.55). Oppositely, in condition B and C, they reported higher engagement in overall experiences (B: MD = 6.0, SD = 1.31, C: MD = 6.0, SD = 1.60) with lower ratings on X-axis (B: MD = 5.0, SD = 1.24, C: MD = 5.0, SD = 1.20) and Y-axis (B only: MD = 5.0, SD = 1.41).

Consistent with an overall moderate to high engagement across conditions, participants felt moderately present in the virtual environment throughout the study (see Figure 4). Specifically, they felt more present in condition A with regards to general presence (GP, M = 5.05, SD = 1.50), Spatial Presence (SP, M = 5.26, SD = 1.63), and Involvement (INV, M = 4.81, SD = 1.71). When they moved their heads wider in condition C, they consistently felt least present (GP, M = 4.95, SD = 1.46; SP, M = 4.95, SD = 1.75; INV, M = 4.49, SD = 1.80). However, we found no significant differences across ranges. Additionally, we found a similar descending trend in the ratings of the pragmatic quality of the task (A: M = 6.02, SD = 1.26; B: M = 5.69, SD = 1.42; C: M = 5.31, SD = 1.60) as well as the level of concentration (A: M = 5.76, SD = 1.41; B: M = 5.43, SD = 1.57; C: M = 5.19, SD = 1.63), as the head movement range increased from condition A, B, to C. The hedonic quality was comparable across conditions. A RMANOVA revealed statistical significance across ranges in the pragmatic quality, F (1.75, 145.5) = 13.2, p <.001, ω^2 = 0.037. Post hoc tests showed that its ratings decreased significantly with motion range, A - C (mean difference = 0.714, p <.001), B - C (mean difference = 0.381, p <.05).

4.4 Subjective Comments

In the final semi-structured interview, participants were asked about their overall VR experience, the dwell-time durations, the potential for daily use, and their preference between head-gaze-based interaction and hand-held controllers. Two experimenters developed a set of recurring themes, using thematic analysis on the original notes and recordings as demonstrated in [6]. The resulting themes are listed below along with direct quotes identified with user IDs.

Motion Sickness vs. Engagement. None of the participants experienced severe symptoms of motion sickness throughout the study. In the interview, five participants felt *"...no motion sickness at all but just uncomfortable"-P13*. They associated motion sickness with discomfort and reported cumulative feelings of discomfort after the rear-seat VR, such as *"...I didn't felt any sickness during the VR experience, but I felt motion sick after taking off the headset"-P3*. This suggests that the more concentrated participants are on the task, the less motion sickness occurs during the VR experience. Six participants were *"...engaged, but still aware of the real world because of the car movements and the highway sounds"-P9* and one was even concentrated *"...on the car movements and sounds and tried to imagine the current location in the real world"-P10*. Although we incorporated continuous nature sounds and sound effects into the HMD task, the noises from the car and highway disrupted the participant's feeling of presence. Nevertheless, three participants felt the most engaged in condition A since *"there was more time to look around in the virtual environment..."-P1* due to the slowest pre-programmed speed, and further *"...discovered more objects in the background of the virtual environment"-P2* in this smaller range. The other three felt most engaged in the first condition since they were new to the task and had the highest level of concentration regardless of the tested range.

Yaw (X) vs. Pitch (Y) axis. When asked to compare their overall head movement experience on the yaw and pitch axes, participants assessed the yaw movement (MD = 6.0, SD = 0.59) more positively than the pitch axis (MD = 4.0, SD = 1.42) with 1 indicating "strongly negative" and 7 for "strongly positive". Nine participants found the yaw movement *"...easy and more natural"-P8*, while three described the pitch movement *"uncomfortable"-P1* and had to *"...move the body to reach the target"-P4*. Furthermore, five participants bumped into

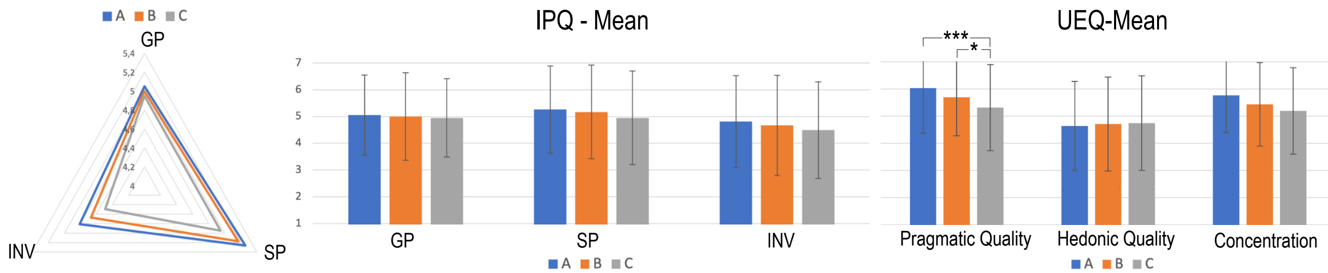

Figure 4: The means of igroup Presence Questionnaire (IPQ) and user experience questionnaire-short (UEQ-S) across all conditions. * indicates a significant difference between two conditions with $p \leq 0.05$, * for $p \leq 0.001$.**

the car ceiling or the side door in condition C while moving their heads by ±65°. They reported that *"...when I crashed into the car roof I didn't felt engaged"-P8* as well as *"...looking up and down made me feel the weight of the HMD"-P20.* This wider head movement made them aware of the real world and decreased the feeling of presence.

Dwell-Time Duration. Participants preferred 0.3s (n=9) and 1s (n=10) to the long dwell-time duration of 3s (n=1). The single participant couldn't distinguish between the short and middle duration. Our results from this head-gaze-based task in a mobile field study align with prior VR studies suggesting 1s or less for simple tasks [2, 4, 21, 48]. Some participants found the preferred duration *"...more efficient"-P10* and *"...easier to concentrate on the task and less motion sick"-P1.* Ten participants disliked the long duration of 3s that was *"...boring and unresponsive"-P18*, especially in condition C as *"...the neck had to rest longer in an uncomfortable position"-P21.* However, it offered others *"...the most time to explore the surrounding virtual environment with the eyes"-P6.* As a trade-off, the middle duration of 1s was viewed as *"...a good balance between the short and long dwell-time"-P19*, whereas the short duration of 0.3s as *"...engaging but led to too much movement"-P19.* Taken together, for the implemented dwell-time-based interaction in rear-seat usage of HMD, the 1s was reported as *"...less stressful"-P1* and *"...more relaxing"-P17* than the 0.3s.

5 INSIGHTS FOR REAR PASSENGER MOTION SICKNESS WHEN USING HMDS

Based on the data analysis, we present two design guidelines and one future research direction for rear-seat HMD applications: i) Design the main interaction area, e.g., the major virtual display(s), which defines the passenger's most frequent head movements, within ±50° along the X- and Y-axis; ii) Design the UIs beyond the activities and consider the visual cues to guide the passenger's head movements for counteracting motion sickness; iii) Our automotive virtual field study approach may be a future research direction for investigating motion sickness in rear-seat HMD usage.

5.1 Trade-off regarding Head Movements

Based on our statistical analysis of the ECG data, we found significant differences between the baseline and three conditions regarding RMSSD and SI. This means that participants felt significantly more sick after putting on the HMD. Although we found no significant differences across ranges, compared to B and C, condition A caused the lowest RMSSD and highest SI, which is a physiological indicator for motion sickness. However, in the subjective reports, we found that the SSQ means increase when the range widens, and participants rated themselves most motion sick in condition C. They concentrated less on the task and rated the pragmatic quality of the interaction worse with wider movements. This descending order reflected in the significant differences between condition A and C in the ratings of comfort and motion sickness. The engagement and hedonic quality of the experience were comparable across ranges. Meanwhile, condition B (±50°) performed moderately well in both physiological and subjective measurements, which we consider the best trade-off between motion sickness and engagement.

5.2 UIs in HMDs for Counteracting Motion Sickness

Following the key determinant of the display size, position and content [13, 14], we implemented a virtual display (head-gaze-based targets and the progress bar) with a cross shape of 27.4 cm width and a length ranging from 1.92 m (A), 4.88 m (B), to 8.80 m (C). The cross shape display is located at a distance of 2.05 m from the position of the main camera. The display shows the content of a moving low-poly bird to guide the passenger's head movement and a hover area with an identical size of the red square target. Participants' voluntary movements indicate an optimal range for task performance with a slight difference between the X axis and Y axis, namely 25° to 50° on the X-axis and smaller than 25° on the Y-axis. Given the individual difference in the inherent susceptibility to motion sickness, we envision an adaptive display in HMDs. For example, based on the detected real-time performance of rear passenger's head movements, the UI could trigger a guidance mode in which the user can follow the emerging visual motion cues in the peripheral area [39], synchronised with the real-time car movements, displayed within a limited range of head/gaze movements, and subtly integrated into the background of the virtual environment.

5.3 Study Methodology

Faced with the upcoming concept of self-driving carsickness, future research will probably address large and multiple displays integrated into autonomous cars, HMDs, or even head-worn see-through displays with numerous placements and sizes of virtual displays in the ultimate augmented reality display. Our work demonstrates the feasibility of conducting a field study for investigating the rear-seat passenger use of HMDs on the way. In a follow-up study, we plan to render a mix of the real-captured environment (e.g., car interior, traffic context) and virtual environment (e.g., six virtual displays in a cross) in the VR HMD to simulate future see-through displays and to further examine the generalizability of our results on motion sickness from VR HMD to see-through displays. Back to current research on carsickness, it scales from a field study (UI tests on physical displays e.g., watching movies on an integrated tablet) to a laboratory study (simulate the car movements via a motion platform, e.g., 4D motion chair [51]). Here, we envision a semi-fidelity study approach adapted from the virtual field study by Mäkelä et al. when investigating large displays in public space [35]. This approach, when used in the automotive context, can potentially fill the gap of carsickness research with the real traffic environment and simulated UI tests in VR HMDs, along with advantages such as saving the cost of building large physical displays, flexible design of UIs, and the potential for peripheral visual motion cues to mitigate motion sickness [39].

6 LIMITATIONS AND FUTURE WORK

Finally, we would like to reflect on some limitations in our rear-seat VR field study. We used an accessible VR HMD, the Oculus Quest with its specific technical parameters. A newer model with a wider FoV, higher resolution and refresh rate might improve the user's visual perception, reduce simulator sickness, or further influence our results on motion sickness and engagement. Other limitations concern our sample, implemented prototype, and testing environment, which were partly unavoidable because of the ethical and safety concerns involved in such a field study using the HMD in a moving vehicle. Throughout the study on the highway, participants were exposed to potentially severe motion sickness with a superposition of carsickness from the moving car rear seat and simulator sickness from wearing the HMD in multiple conditions. Faced with the challenge of balancing an effective elicitation of motion sickness while ensuring our participants' ethical and physical safety, we prescreened for vulnerable participants and thus limited and skewed our sample. Moreover, these participants probably become the first generation of consumers adopting the in-car HMD technology. Consequently, our results might have changed if we had tested with a larger number of participants with a higher level of proneness to motion sickness. Out of safety concerns in this field study, we selected a city highway, with relatively controlled traffic conditions in comparison to stop-and-go traffic on urban streets or winding roads in the countryside. Our results are, therefore, limited to such a traffic environment, namely using the HMD in a moving car at a constant, moderate speed. Besides, the differences in the observed motion sickness across head ranges might be associated with the actual driving profile, such as slightly changing bumps. We call for an in-depth investigation on the diverse combination of different profiles of head movement and vehicle motion, such as the association between the vehicle dynamics and the speed and amplitudes of head movements. To investigate passenger head movements independent of mitigation strategies in HMDs, we cautiously designed an in-congruent rear-seat VR experience combining a stationary virtual environment (fixed camera position in an abstract landscape) and a moving real environment (motion profiles of the car) but without synchronised visual motion cues [39]. These visual cues might mitigate the identified motion sickness, which remains to be verified in a follow-up study. Moreover, our current VR prototype achieved only a moderate level of presence across groups. Future studies can explore the design of the head-gaze targets embedded into the virtual environment to enhance the presence during the rear-seat VR experience. We analysed the discrete level of head range to control the severity of motion sickness in this exploratory field study. In a follow-up study, we plan for a continuous head range, such as a slider along the X- and Y-axis, to lift restrictions on the freedom of head movement in reality. Regarding the general study design, a stationary vehicle setup could help tease apart the compound influences of vehicle motion and head movements on motion sickness. Similarly, future studies can explore more sensitive physiological measurements of motion sickness to improve the study validity by controlling the potential impact of physical activity. In addition, the concept of feeling of safety [34] while using the HMD in the car is worth further investigation.

7 SUMMARY

The term "self-driving carsickness" aims to distinguish this phenomenon from the traditional carsickness considering its multifaceted causes [13, 14]. Increasing use of large, multiple displays integrated or brought into the car might amplify one facet of future self-driving car-sickness. Such motion sickness will become a superposition of physically induced car sickness and VIMS [5]. In this rear-seat VR field study on a city highway, we explored the influence of head movements on motion sickness and the feeling of engagement in their use of a HMD. Three implemented conditions (A, B, C) share the orientations of yaw and pith head movements and frequency of $0.2\ Hz$ but differ in the required range of head movements (±25°, ±50°, ±65°). To control input modalities in VR, we used head-gazed-based interaction and a dwell-time-based interface with dwell durations of $0.3s$, $1s$, and $3s$. Based on the recorded physiological and subjective data, we found a good trade-off for rear-seat passenger head movement, characterised by the range of ±50° (with the speed of $1.95m/s$), a preferred motion around the yaw (X) axis, and a dwell-time duration of $1s$. It is essential to consider the basic perceptual mechanism of motion sickness in the automotive UI design process, especially for the rear-seat passenger in anticipation of self-driving cars. Our exploratory work focuses on rear-seat passenger motion sickness and offers a concrete starting point for future carsickness studies of automotive display technologies such as HMDs or head-worn see-through displays.

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