The Influence of In-Vehicle Display Locations on Motion Sickness

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ABSTRACT

As smart cabins become more prevalent, various displays have been embedded in vehicles to enhance the occupants' experience. However, in-vehicle displays may also increase the risk of motion sickness (MS) among occupants due to prolonged exposure to conflicting sensory stimuli. Though previous research has shown a connection between MS and visual motion cues, particularly those related to road visibility, it remains unclear whether and how display location, as an interface design factor, influences passengers' motion perception through peripheral visual information and head motion, thereby contributing to MS. Thus, to guide the design of smart cabins, a within-subject on-road experiment was conducted to explore the relationship between display locations (including roof, backrest, and armrest displays), view conditions (unblocked view with road environment versus blocked view) and MS development. Results showed that the external-view condition was associated with lower MS than the view-blocked condition, consistent with the importance of maintaining peripheral access to road-motion cues. When passengers had an unblocked external view, the roof display was associated with the lowest MS, likely because it supports better peripheral visual motion information, situational awareness, and anticipation of upcoming vehicle motion. Even when the external view was fully blocked, the roof display still outperformed the other locations, possibly because it induces head posture and head-motion patterns that may reduce sensory conflict. These findings provide evidence-based insights into smart cabin interface design, highlighting the role of display placement in shaping peripheral motion perception and head posture to mitigate MS.

Keywords: motion sickness; display location; on-road study; smart cabin

1. Introduction

The development of technologies such as Information and Communications Technology (ICT) and artificial intelligence (AI) has made In-Vehicle Infotainment Systems (IVISs) increasingly popular in smart cabins (Faurecia, 2023 , see Table 1). As a result, occupants may spend more time engaging in non-driving-related tasks (NDRTs), such as work or in-vehicle entertainment. To support these activities, displays are being integrated into diverse locations within the vehicle cabin—including roofs, seat backs, and center consoles—beyond traditional front-dashboard positions. This transformation has gradually shifted vehicles from a means of transportation to a “third space” beyond homes and workplaces, with potential societal benefits. For example, survey studies in the 45 largest cities in China revealed that individuals’ average daily commuting time is around 72 minutes (YueXiAn, 2023). If this commuting time can be effectively utilized for work or entertainment, overall social efficiency can be improved. Accordingly, industry projections anticipate that IVIS market share will surge from $16.4 billion in 2023 to an estimated $28.3 billion by 2028 (MarketsandMarkets, 2023), indicating growing demand for in-vehicle digital interaction. However, the placement of these interfaces may have unintended consequences for passenger comfort, particularly with respect to motion sickness (MS), warranting careful investigation of how display location affects occupants during vehicle motion.

MS, characterized by physical discomfort during passive body movement, is associated with symptoms such as malaise, nausea, and, in severe cases, emesis (Smyth et al., 2021). It is prevalent in various modes of transportation, including aviation (Turner et al., 2000), rail transport (Suzuki et al., 2005), sea transport (Lawther & Griffin, 1986), and vehicle transport (Xie, He, et al., 2023). Survey studies have reported that 59% of individuals had experienced in-vehicle MS at least once in their lifetime (Schmidt et al., 2020), while more recent data from China indicate that over 70% of respondents experienced MS in the past year (Xie et al., 2024). Previous studies have further shown that engaging with in-vehicle displays, such as watching videos, increases the likelihood of MS (Kato & Kitazaki, 2006). This effect may stem from a reduced ability to perceive vehicle motion through peripheral visual information and a diminished awareness of vehicle dynamics while focusing on visual secondary tasks (Xie, He, et al., 2023). Consequently, substantial research efforts have sought to mitigate MS among vehicle occupants, particularly when they are engaged in in-vehicle activities. Previous studies have demonstrated that maintaining visual access to the external road environment or providing supplementary motion cues, such as dynamic visual indicators on smartphone displays (Meschtscherjakov et al., 2019) or in virtual reality (VR) displays (Qiu et al., 2022), can reduce MS severity levels.

However, MS in vehicles can be a compound effect of sensory conflict (i.e., inconsistencies among visual, vestibular, and proprioceptive cues about self-motion and orientation, Reason, 1978) and motion accumulation (Donohew & Griffin, 2004). Thus, providing motion cues alone may not fully alleviate the MS of occupants. Hence, previous research has also examined how display locations influence MS development in vehicles in human-computer interaction (HCI) studies. For example, a head-up display (HUD) has been found to provide better road visibility and to help passengers perceive motion information and predict future vehicle movements more effectively than a head-down display (Diels & Bos, 2016). However, this previous study focused on front-seat occupants and explored only a limited number of display locations. Recently, smart cabins have adopted a wider range of display locations, especially for rear-seat occupants, underscoring the urgent need to determine which locations are preferable for MS induction. Thus, it is necessary to consider the display location from an HCI perspective, i.e., treating the display location as an interface design factor that constrains head posture and alters the availability of peripheral visual motion cues. Specifically, head posture can alter the absolute vestibular stimulation acting on the head, thereby contributing to MS development, while the peripheral visual motion cues can affect passengers' ability to anticipate upcoming vehicle motion, thereby modulating sensory conflict during driving.

Accordingly, this study investigates how different display locations, as interface design choices, influence MS development in smart cabins, given that the interface location may affect MS through postural (by shaping passengers' head posture) or perceptual (by shaping passengers' perception of peripheral visual motion cues) pathways. We conducted an on-road experiment to explore how three commonly used display locations (see Figure 1): (1) a roof display, mounted at the center of the vehicle roof above the first row and oriented vertically to the floor, requiring a right rear passenger to look up towards the upper left corner (Li Auto L9; Li Auto, 2022); (2) a backrest display, positioned at the eye level of rear-seat passengers and also vertically aligned with the floor (Jeep Grand Wagoneer; MotorTrend, 2023); (3) an armrest display, installed between the front seats at a 70° inclination to the floor, requiring a right rear passenger to look down towards the lower left corner (Tesla Model S/X; Cristovao, 2021). Hence, we formulate our first research question (RQ1): which display location would result in less MS in the smart cabin? Further, given that many luxurious vehicles now have a blocked cabin without external views (Lam, 2018), we have our second research question (RQ2): how the view condition may interact with the display location (i.e., whether we need different display locations for a blocked cabin).

2. Literature Review

2.1 Visual Motion Perception and Motion Sickness

Visual conditions play a critical role in MS development, as they determine how vehicle motion is perceived. A meta-analysis of experimental studies indicates that internal-view conditions, where side and front windows are blocked, and visual self-motion cues are removed, can lead to significantly higher MS than external-view conditions, where passengers can observe the road environment and perceive vehicle motion visually (Xie, He, et al., 2023). This difference is commonly attributed to the availability of visual motion information that reduces visual–vestibular conflict. Similar mechanisms have been used to explain the elevated MS levels observed when passengers engage in visually demanding tasks, such as watching videos, during vehicle travel (Isu et al., 2014). These findings highlight the importance of peripheral visual motion cues in supporting accurate perception of vehicle dynamics.

2.2 Head Motion and Motion Sickness

Previous studies have consistently demonstrated that head movement and head posture play an important role in MS development. Previous studies indicated that head posture plays an important role in MS, with actively controlled head alignment delaying symptom onset, whereas passively imposed alignment has the opposite effect (Golding et al., 2003). Vehicle-based interventions, such as chassis lean and centripetal head tilt, have similarly been shown to reduce MS severity (Sugiura et al., 2019; Wada et al., 2012; Wada & Yoshida, 2016). These findings suggest that head movement affects MS.

From a modeling perspective, this relationship is also consistent with the six-degree-of-freedom subjective vertical conflict (6-DoF SVC) theory, in which MS risk is determined by the accumulation of acceleration signals expressed in a head-fixed coordinate system (Kamiji et al., 2007). Changes in head posture alter the orientation of this coordinate system and, consequently, influence the predicted level of sensory conflict and MS risk. Inspired by this framework, Xie, Yan, et al. (2023) conducted simulation studies showing that display location can indirectly affect MS by inducing different head postures, thereby modifying head-fixed motion dynamics.

2.3 Display Location as An Interface Design Variable

According to the sensory conflict theory, MS occurs when motion information provided by the visual and vestibular systems is inconsistent (Reason, 1978). Thus, human-machine interfaces (HMIs) have been extensively investigated to alleviate MS in vehicular settings by enhancing occupants' perception of vehicle motion. Prior HCI studies have shown that anticipatory visual cues, such as in-cabin LED light strips (Karjanto et al., 2018), and auditory motion cues (Maculewicz et al., 2021) can reduce MS by improving awareness of upcoming vehicle movements. Emerging display technologies, including virtual reality (VR) and head-mounted displays (HMDs), have also been investigated in vehicular contexts. For example, road-aligned virtual environments (Cho & Kim, 2022) and earth-fixed HMD presentations (Sato et al., 2022) have been shown to reduce MS compared with visually unstable or head-fixed HMDs.

Beyond the content of motion cues, interface design, especially the display location, can influence MS through multiple perceptual pathways. Previous studies have reported that the spatial placement of in-vehicle displays can significantly affect visual attention allocation and viewing geometry during real-road driving (Hada, 1994), and that the display placement can also alter head posture during sustained visual tasks (Rempel et al., 2007). Such differences in visual access and head posture may, in turn, influence motion perception and discomfort during in-vehicle interaction. As noted previously, existing findings have largely focused on front-seat scenarios and may not generalize directly to rear-seat occupants in smart cabins, where peripheral visual access and head postural constraints differ substantially. As modern smart cabins increasingly integrate diverse rear-seat display configurations, a systematic investigation of how display location influences motion perception and MS development in these emerging interaction contexts is needed, especially given that seat position (front passenger versus rear seat) can influence MS (Schmidt et al., 2020).

3. Methodology

3.1 Participants

A total of 24 participants (12 males and 12 females), recruited through online forums and in-campus posters, participated in the experiment, with a mean age of 21.0 (min: 18, max: 31, standard deviation (SD) = 3.4). They were required to self-report having high susceptibility to MS scores, as defined as over the 75th percentile of MS Susceptibility Questionnaire Short-form (MSSQ-Short) score (Golding, 2006), i.e., at least 19 out of 54 points in MSSQ-short (Lim et al., 2021). This is because individuals with higher MSSQ scores are more likely to experience MS in vehicles, and thus, the effect of experimental control can be more observable. Given that the experiment was conducted in mainland China, the Chinese version of MSSQ-short was used for the participant selection (Lin & Guo, 2022). Ultimately, the mean MSSQ score of participants was 28.1 (min: 19.1, max: 47.0, SD = 7.0). All participants are self-reported to be healthy and exhibit normal vestibular functions. To avoid bias in subjective reporting, participants were not informed of the specific study hypotheses regarding display location and MS; instead, they were simply instructed to engage in a video-watching task while moving in a vehicle.

A priori power analysis was conducted using G*Power 3.1 (Kang, 2021). For the primary within-subject analysis with 6 experimental conditions (3 display locations ×

2 view conditions), assuming a medium effect size (f = 0.25), α = 0.05, correlation among repeated measures (ρ) = 0.5, and sphericity (ε = 1), the required sample size to achieve 80% power was N = 19.

3.2 Equipment

We utilized a fuel-engine Volkswagen Magotan as the instrumented vehicle (see Figure 2a) with a 12.9-inch iPad as the in-vehicle display. The iPad was securely mounted using a specialized holder to prevent relative motion of the iPad to the vehicle during the trials. We also manually checked the location of the iPad before each ride to ensure consistent location and orientation across all trials. As mentioned, three locations of the display were explored following benchmarking vehicles, specifically:

(a) The **roof display** (Figure 1a) simulated entertainment screens in vehicle models such as Li L9 (Li Auto, 2022). It was vertically mounted along the symmetry midline of the vehicle. The distance between the basement of the holder to the headrest of the right rear seat was approximately 95 cm.

(b) The **backrest display** (Figure 1b) simulated entertainment screens in vehicle models such as the Jeep Grand Wagoneer (MotorTrend, 2023). It was vertically mounted and aligned with the middle line of the headrests of the front passenger seats.

(c) The **armrest display** (Figure 1c) simulated entertainment screens in vehicle models such as the Tesla Model S/X (Cristovao, 2021). It was inclined at an angle of 70° relative to the horizontal surface and mounted along the middle line of the glove compartment.

(a) (b)

(c) (d)

Figure 1. Locations of the displays and the experiment setups: a) roof display; b) backrest display; c) armrest display; d) blocked view.

(a) (b)

Figure 2. The instruments used for the study: a) Instrumented vehicle used for the on-road data collection; b) The position of the IMU recording the vehicle dynamic profile.

In the blocked view condition, the side windows, front view, and top view were occluded by curtains on the side windows, a board between the first and second rows, and a sunshade for the car sunroof, respectively (see Figure 1d). An IM948 Inertial Measurement Unit (IMU) was affixed to the horizontal surface of the glove compartment in the middle of the first row (see Figure 2b), which collected linear and angular acceleration at a frequency of 30Hz, with accuracies of 0.01G and 0.05°/s, respectively. Following the right-hand coordinate system as per ISO8855 (2011), the z-axis, x-axis, and y-axis are pointed upwards, front, and right of the vehicle, respectively.

3.3 Experimental Tasks

In the experiment, participants took rides in the instrumented vehicle, consistently driven by the same operator (the first author) to ensure uniform driving behavior across different trials. The vehicle followed a predetermined urban route on the outer ring of the University City, Guangzhou, China, with a fixed duration of around 40 minutes (see Figure 3). To minimize the impact of traffic flow on the results, the experiments were conducted only during non-rush hours, i.e., on weekdays between 9:00 am and 4:00 pm. The road features six lanes in each direction and has a design speed of 30-60 km/h. The mean of average speeds across all trials was 32.6 km/h, with a standard deviation of 2.3 km/h.

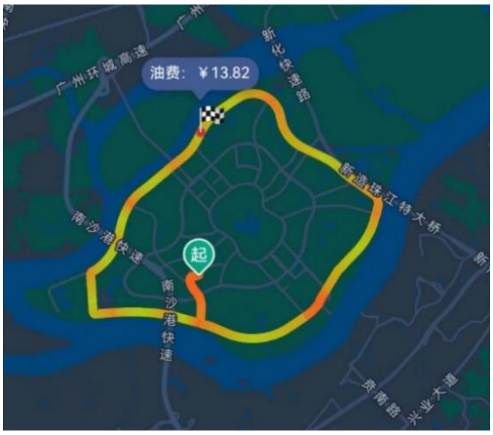


Figure 3. The predefined route for the ride in the University City, Guangzhou, China

During each ride, the in-vehicle display played documentary video clips related to food, history, culture, or military. During the rides, the sole task that was allowed other than reporting the MS levels was this video-watching task. All the video clips were in Chinese, the native language of the participants, thereby minimizing potential comprehension challenges. All participants were informed that the questions related to the video would be asked after the rides, and their bonus would be based on their answers, to encourage the participants to concentrate on the videos. The questions were designed to encompass the entire duration of the 40-minute videos and were non-common knowledge so that participants could hardly answer them without watching the videos. The video clips varied across rides for a given participant (so that they had to focus on the videos in all rides), but the order of the videos remained consistent for all participants, thereby canceling out the potential impact of video content on the MS (see Figure 4) when a Latin square experiment design was used for other experimental conditions.

3.4 Experiment Design

A within-subject experiment design was adopted with two factors, i.e., display location (i.e., roof display, backrest display, and armrest display) and view condition (i.e., blocked and unblocked view), leading to six experimental conditions and hence six rides for each participant. To mitigate habituation effects and allow participants a sufficient recovery period if MS occurred during a ride, a minimum gap of 3 days was implemented between rides for each participant. To mitigate the order effects, the experimental conditions were counterbalanced based on a Latin square design (Figure 4), leading to six orders in total. Four participants (2 male and 2 female) were assigned to each experiment condition. Thus, in total, we collected data from 144 rides, i.e., 6 orders by 4 participants (2 male and 2 female) per order, and 6 rides per participant.

F1 & F2 & M1& M2	A	B	C	D	E	F
F3 & F4 & M3 & M4	B	C	D	E	F	A
F5 & F6 & M5 & M6	C	D	E	F	A	B
F7 & F8 & M7 & M8	D	E	F	A	B	C
F9 & F10 & M9 & M10	E	F	A	B	C	D
F11 & F12 & M11 & M12	F	A	B	C	D	E

Figure 4. The Latin square design of the experiment. A to E represent different combinations of view conditions and display locations, while blocks with the same color indicate the same video clip played during the rides. F1–F12 denote the twelve female participants, and M1–M12 denote the twelve male participants.

3.5 Experiment Procedures

Following the guidelines by Suwa et al. (2022), at least one day before the experiment, all participants were instructed to:

(a) Prioritize self-care to maintain good health.

(b) Ensure sufficient sleep the night before to prevent drowsiness.

(c) Avoid alcohol intake the day before to avoid residual effects.

(d) Finish meals at least 1 hour before the experiment, maintaining a balanced state of neither hunger nor fullness.

On the day of the experiment, upon arrival, each participant signed a consent form informing the objectives, procedures, associated risks, and potential benefits of the experiment. They were explicitly informed of their right to withdraw from the experiment at any point, particularly if they were unable to endure MS-induced nausea. If this happened, we stopped the car at the nearest safe location, and they were allowed to exit the vehicle. The experimental ride would then be terminated. Before the ride, participants were provided with an explanation of a Chinese version of the Misery Scale (MISC; Lin & Guo, 2022), which measures respondents' level of MS (Bos et al., 2005, see Table 1).

During the ride, as mentioned, participants were required to watch video clips on an in-vehicle display. At the same time, a timer, emitting an auditory alert (with a loudness of 90 dB, frequency of 1000 Hz, and duration of 1 second) at minute intervals, prompted participants to report their MS levels orally using the MISC. To remind the participant of the meaning of the scale, the MISC was printed and stuck on the frame of the screen (see Figure 1d). To maintain consistency, in all rides, the cabin environment was controlled by setting the wind speed at level three and a temperature ranging between 25 and 27 degrees Celsius. Further, the positioning and inclination of the chair remained constant across all trials, and the audio narration in the video was set to a constant level.

The experiment would stop when we reached the destination of the route (around 40 minutes), when the participants requested to stop, or when the MISC scores exceeded 7 (i.e., "Rather Nausea"). The MISC of 7 was commonly adopted as the stopping threshold in previous MS-related studies (Irmak et al., 2021; Suwa et al., 2022). Following the conclusion of each ride, participants answered questions regarding the video they watched during the ride. All participants received monetary compensation at a rate of 60 Yuan per hour, regardless of the correctness of their answers, but they would only receive full compensation after they finished all six rides. All participants provided written informed consent before participating in the study. This protocol received approval from the Human and Artefacts Research Ethics Committee of the Hong Kong University of Science and Technology (HREP-2023-0193).

Table 1. MISC for evaluation of MS during the rides

Symptoms		MISC
No problems		0
Some discomfort, but no specific symptoms		1
Dizziness, cold/warm, headache, stomach/throat awareness, sweating, blurred vision, yawning, burping, tiredness, salivation, . . . but no nausea	Vague	2
	Little	3
	Rather	4
	Severe	5
Nausea	Little	6
	Rather	7
	Severe	8
	Retching	9
Vomiting		10

4 Data Analysis

4.1 Quantification of Motion Stimuli

To ensure consistency in motion stimuli across experimental conditions, we compared the MS Dose Value (MSDV) across different rides. The MSDV serves as an objective measure to assess MS induced by continuous motion exposure to vehicles (Donohew & Griffin, 2004). Although conducting experiments on public roads can replicate a natural driving environment, there is a concern that variations in vehicle motion and acceleration between rides might obscure the effects of experimental factors. Therefore, to confirm that vehicle motion remained similar across various experimental conditions, we initially compared the MSDV across rides.

The MSDV serves as an approach to assess MS induced by vehicle motion stimuli (ISO2631-1, 1997). The comprehensive $MSDV_{total}$ (Yunus et al., 2021), as defined in Equation (1), was calculated to quantify motion stimuli in a ride.

$$\boldsymbol{MSDV_{total}} = \sqrt{\boldsymbol{MSDV_x}^2 + \boldsymbol{MSDV_y}^2 + \boldsymbol{MSDV_z}^2} \qquad (1)$$

Where $\boldsymbol{MSDV_x}$, $\boldsymbol{MSDV_y}$, and $\boldsymbol{MSDV_z}$ can be calculated as the weighted integral of acceleration in different directions, as shown in Equation (2) and Equation (3).

$$\boldsymbol{a_{i,w}(t) = a_i(t) \times W_i \qquad i = x, y, z} \tag{2}$$

$$\boldsymbol{MSDV_i = (\int_0^T (a_{i,w}(t))^2)^{1/2}} \tag{3}$$

In which, $\boldsymbol{W_i}$ was the weight of the acceleration. In our study, we applied the frequency weighting specified in ISO2631-1 (1997) to compute $MSDV_z$ in the vertical direction and utilized the frequency weightings from Donohew and Griffin (2004) for the calculation of $MSDV_x$ and $MSDV_y$ in the lateral and longitudinal directions. The acceleration data required for MSDV calculations were obtained using the IMU attached to the vehicle's glove compartment, as shown in Figure 2b.

To check the consistency of the motion stimuli across experiments, we compared the $MSDV_{total}$ at four time points during each ride (i.e., 10^{th}, 20^{th}, 30^{th}, and 40^{th} minutes) by fitting four repeated-measures ANOVA models using linear mixed-effects modeling (Lohse et al., 2022). In each model, display location, view condition, and their interaction were treated as fixed effects. Random intercepts were included for participants, as well as for participant-by-display and participant-by-view combinations, to account for within-subject dependencies across repeated measurements. Linear mixed-effects models were fitted using the *lmer()* function to perform repeated-measures ANOVA, allowing both fixed effects of experimental conditions and random effects associated with individual participants to be modeled simultaneously:

$$\mathrm{lmer}(\mathrm{MSDV}_{total} \sim 1 + \mathrm{Display} + \mathrm{View} + \mathrm{Display{:}View} + (1|\mathrm{Participant}) + (1|\mathrm{Participant{:}Display}) + (1|\mathrm{Participant{:}View}))$$

4.2 Influence of Experimental Conditions

We then investigated how display location and view condition can influence MS development. It should be noted that when early discontinuation of the rides happened, we could not predict the MISC score if they had continued the trials. Thus, we padded the MISC value of the rest of the rides using their last reported value based on the assumption that once participants reach a MISC score of 7 or higher, their MISC score will not decrease under ongoing motion stimuli, which is a common practice in MS-related research (Irmak et al., 2021; Kuiper et al., 2018; Kuiper et al., 2020). As a result, it is unfair to compare the MISC scores of participants who stopped earlier and those who finished the rides. Thus, following previous research (Kuiper et al., 2018) that adopted the same early discontinuation strategy, and given that we were specifically interested in factors that can lead to MS over a threshold, we transformed the MISC scores (ranging from 0 to 7) into binary outcomes (0 = no MS, 1 = MS) based on three thresholds, i.e., MISC $\geqslant$ 2, MISC $\geqslant$ 4, and MISC $\geqslant$ 6, corresponding to “mild”, “moderate” and “severe” MS, respectively.

We then constructed three mixed-effects logistic regression models to investigate the likelihood of participants who reported a MISC score of 2, 4, or 6 or higher during a ride. Display location, view condition, time in ride, and their two-way interactions were specified as fixed effects. To account for individual differences in baseline susceptibility and temporal trends, random intercepts and random slopes of time were included for each participant. Mixed-effects logistic regression models were fitted using the *glmer()* function, which extends linear mixed-effects modeling to binary outcomes:

glmer (MS ~ Display + View + Time + Display:View + Time:View
+Time:Display + (1 + time|Participant))

Furthermore, in this model, the time in a ride was a continuous variable, ranging from 1 minute to 40 minutes with a step of 1 minute; while the Display (i.e., display location: roof versus backrest versus armrest display) and View (i.e., view condition: blocked versus unblocked) were categorical variables.

In our study, we utilized the "lme4" package (Bates, 2010) and “glmmTMB” (Bolker, 2019) in R for regression model analyses, including analysis of variance (ANOVA using linear mixed effect model) and mixed-effects logistic regression models. The "emmeans" package in R was used for pairwise comparison (Lenth, 2022) of significant ($p < .05$) main or interaction effects, with the "Bonferroni” method used for p-value correction.

5. Results

5.1 Performance on Video-Watching Tasks

To ensure the participants’ level of engagement in the video-watching tasks did not bias the results, we analyzed the correctness of their answers to the video-related questionnaires (see Table 2). The ANOVA results indicate that there were no significant differences across different experimental conditions ($p > .05$).

Table 2. Accuracy of participant responses to video-related questionnaires

	Roof display	Backrest display	Armrest display
Unblocked view	Correctness: 79.0% SD: 21.3%	Correctness: 88.5% SD: 19.5%	Correctness: 79.2% SD: 23.4%
Blocked view	Correctness: 82.6% SD: 19.7%	Correctness: 83.3% SD: 20.4%	Correctness: 81.3% SD: 18.4%

5.2 Early Discontinuation of Rides

In total, 5 out of 24 participants discontinued at least one ride. In total, 11 out of 144 rides have been discontinued either by the participants (even if the MISC ≤ 7) or by the experimenter due to a high MISC score (i.e., >7). Specifically, one participant discontinued multiple rides under the blocked-view condition: at the 36th minute with the roof display (MISC = 7), at the 24th minute with the armrest display (MISC = 7), and at the 25th minute with the backrest display (MISC = 8). The same participant also terminated a ride under the unblocked-view condition with the armrest display at the 29th minute (MISC = 8). Another participant stopped rides at several points: under the blocked-view condition with the roof display (36th minute, MISC = 8), under the unblocked-view condition with the roof display (30th minute, MISC = 8), with the backrest display (35th minute, MISC = 8), and with the armrest display (32nd minute, MISC = 8). Additionally, one participant terminated the ride under the blocked-view condition with the roof display at the 37th minute (MISC = 7). Finally, two participants discontinued rides in the blocked-view condition with the backrest display at the 36th and 38th minutes, both with MISC scores of 8. Figure 5 further visualizes the early discontinuation rate across different experimental conditions.

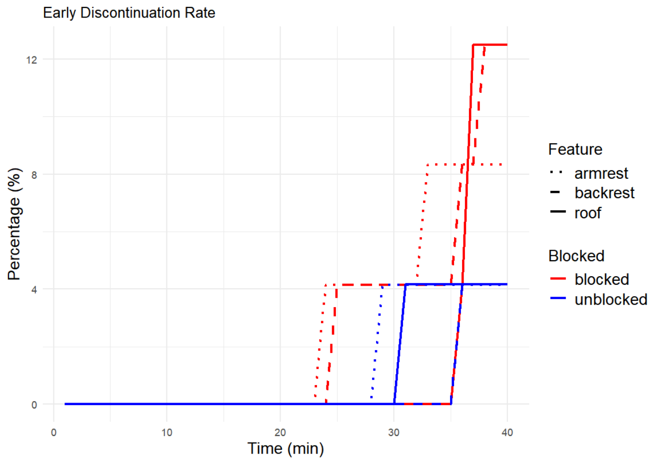


Figure 5. Early discontinuation rate over time across experimental conditions.

5.3 Motion Stimuli

As shown in Figure 6, the ANOVA test revealed that the experimental conditions had no significant (p>.05) effects on the vehicle motion (i.e., $MSDV_{total}$) from the start of the ride (at minute 0) to the 10th minute, 20th minute, 30th minute, and 40th minute, indicating the homogeneity of the vehicle motion across all experimental conditions. Further details regarding the angular velocity (Figure A.2), linear acceleration (Figure A.3), average speeds of the drives (Figure A.4), and aggressive driving behaviors (Figure A.5) in different experimental conditions are reported in the Appendix.

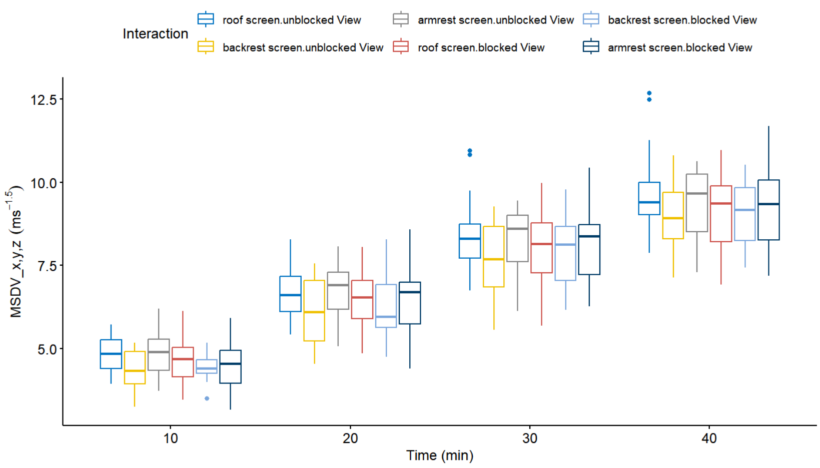


Figure 6. Boxplots of $MSDV_{total}$ across experimental conditions over time. In this figure and the following figures, the boxplot represents the minimum, 1st quartile, median, 3rd quartile, and maximum.

5.4 Subjective Motion Sickness

The average MISC of all trials across different experimental conditions is shown in Figure 7.

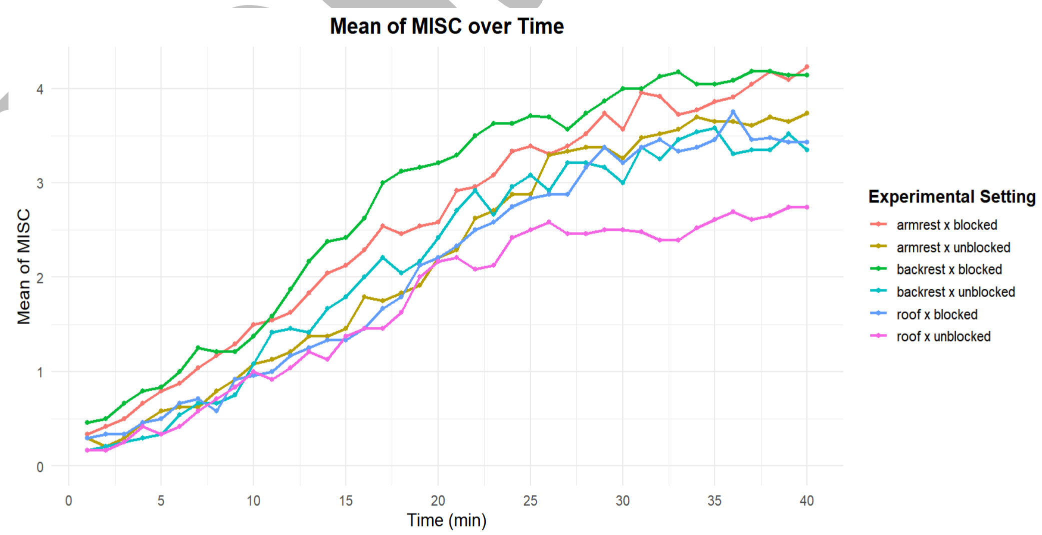


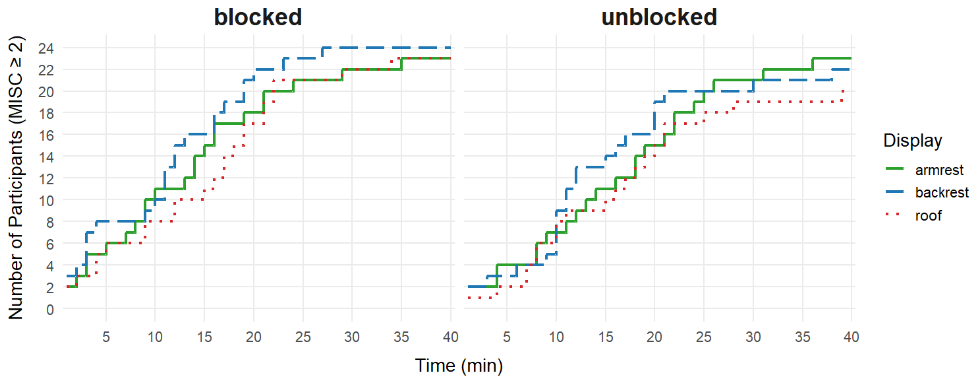
Figure 7. Mean MISC scores across different experimental conditions, including all trials. The values after discontinuation were marked as missing.

Figure 8 shows the number of participants who met a specified threshold for illness rating at the time of measurement. Figure A.1 further illustrates the fluctuation in MISC scores for each participant throughout the ride under each experimental condition. The results of the three mixed-effects logistic regression models with MISC thresholds of 2 (Model 1), 4 (Model 2), and 6 (Model 3) are summarized in Table 3. As mentioned, these models investigated how display location, view condition, time, and their two-way interactions can influence the likelihood of participants experiencing MS, with the MISC score being equal to or over a threshold.

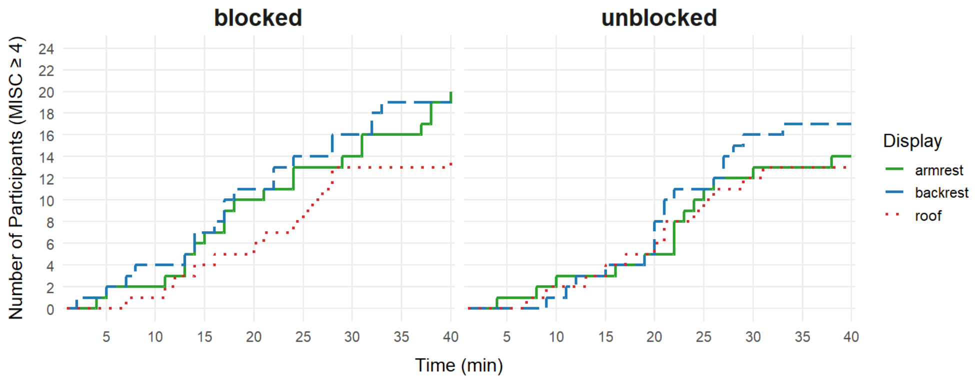
Table 3. Model results of M1, M2, and M3 models

	Parameters	χ^2	DF	*p*-value
M1: Likelihood (MISC ⩾ 2)	time	72.92	1	**< .0001*** **
	View	3.95	1	**.047***
	Display	20.21	2	**< .0001*** **
	View*Display	6.99	2	**.03***
	time*View	9.09	1	**.003****
	time*Display	11.76	2	**.003****
M2: Likelihood (MISC ⩾ 4)	time	27.22	1	**< .0001*** **
	View	1.50	1	.2
	Display	5.97	2	.051
	View*Display	16.98	2	**.0002*****
	time*View	0.60	1	.4
	time*Display	9.47	2	**.009****
M3: Likelihood (MISC ⩾ 6)	time	6.51	1	**.01***
	View	2.67	1	.1
	Display	22.48	2	**< .0001*** **
	View*Display	14.74	2	**.0006*****
	time*View	21.54	1	**< .0001*** **
	time*Display	22.01	2	**< .0001*** **

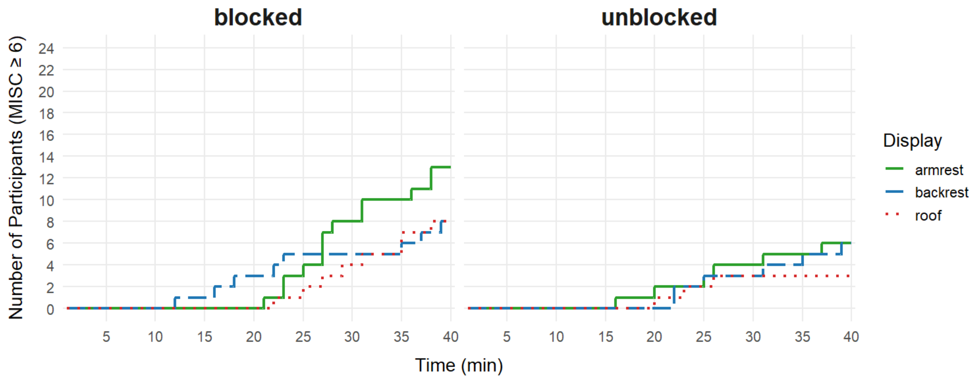
Note: In this table and the following tables, *: $p < .05$, **: $p < .01$, ***: $p < .001$



(a)



(b)

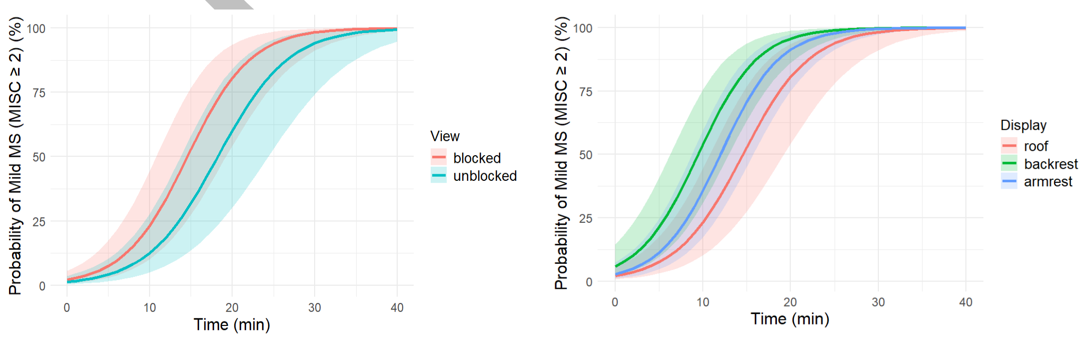


(c)

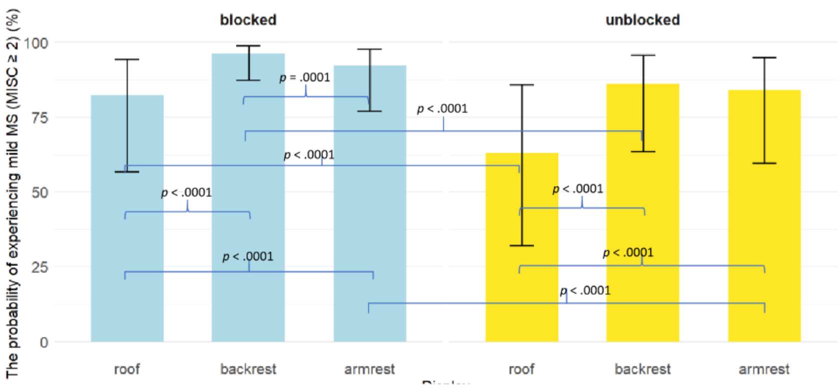
Figure 8. Number of participants experiencing MS, with a) MISC ≥2; b) MISC ≥ 4; and c) MISC ≥ 6.

5.4.1 M1 Model with MISC Threshold of 2

For M1, three significant interaction effects were observed, i.e., between view condition and time, between display location and time, and between display location and view condition. Specifically, the time effect was significantly greater in the blocked view condition than in the unblocked view condition, with an odds ratio (OR) of 1.03, 95% confidence interval (95% CI): [1.01, 1.05], $\chi^2(1) = 9.09$, $p < 0.003$ (see Figure 9a). In other words, with each additional minute, the odds of experiencing mild or higher MS (MISC ⩾ 2) increased approximately 3% faster in the blocked view condition as compared to in the unblocked view condition. At the same time, for the interaction between display location and time, the roof display was associated with a 3% slower increase (OR = 0.97, 95% CI [0.94, 0.99], $\chi^2(1) = 8.08$, $p = .012$) in the likelihood of participants experiencing slight or higher MS (MISC ⩾ 2) compared to the backrest display for each additional minute (see Figure 9b). Similarly, the roof display showed a 3% slower increase (OR = 0.97, 95% CI [0.94, 0.99], $\chi^2(1) = 9.26$, $p = .007$) than the armrest display.



(a) (b)



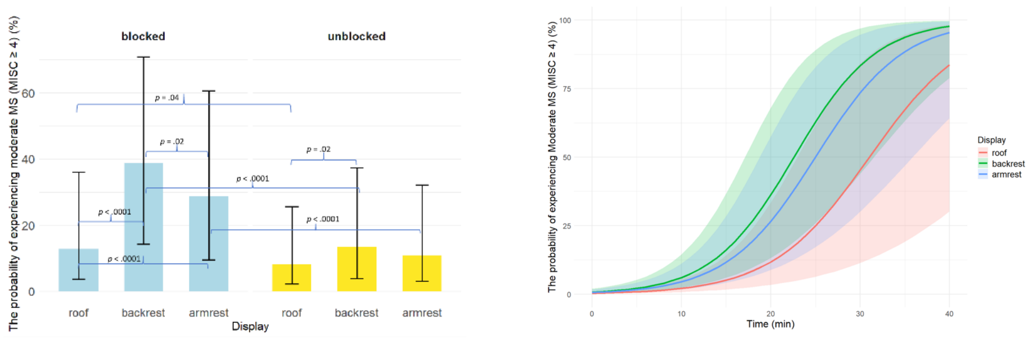
(c)

Figure 9. Interaction effects and estimated marginal means (EMMs) in the M1 model: (a) interaction between time and view; (b) interaction between time and display; (c) interaction between view and display.

As shown in Figure 9c, a significant interaction was observed between display location and view condition. Under the blocked view condition, participants experienced a lower likelihood of mild or higher MS (MISC ⩾ 2) with the roof display compared to both the backrest display (OR = 0.19, 95% CI [0.12, 0.30], $\chi^2(1) = 106.56$, $p < .0001$) and the armrest display (OR = 0.39, 95% CI [0.25, 0.60], $\chi^2(1) = 38.05$, $p < .0001$). In addition, the backrest display was associated with a higher likelihood of MS than the armrest display (OR = 2.08, 95% CI [1.30, 3.33], $\chi^2(1) = 19.89$, $p = .0001$). Similarly, under the unblocked view condition, the roof display again was associated with a lower likelihood of MS than both the backrest display (OR = 0.27, 95% CI [0.18, 0.42], $\chi^2(1) = 74.79$, $p < .0001$) and the armrest display (OR = 0.32, 95% CI [0.21, 0.49], $\chi^2(1) = 58.18$, p < .0001). When comparing view conditions for the same display, the blocked view condition was associated with a higher likelihood of MS than the unblocked view condition for both the roof display (OR = 2.78, 95% CI [1.82, 4.26], $\chi^2(1) = 46.69$, p < .0001) and the backrest display (OR = 4.04, 95% CI [2.55, 6.39], $\chi^2(1) = 75.20$, p < .0001).

5.4.2 M2 Model with MISC Threshold of 4

For M2, two interaction effects were observed, i.e., between display location and view condition, and between display location and time. Specifically, as shown in Figure 10a, a significant interaction was found between display location and view condition. Under the blocked view condition, the roof display was associated with a markedly lower likelihood of experiencing moderate or higher MS (MISC ⩾ 4) compared with both the backrest display (OR = 0.23, 95% CI [0.14, 0.37], $\chi^2(1) = 84.21$, $p < .0001$) and the armrest display (OR = 0.36, 95% CI [0.23, 0.58], $\chi^2(1) = 39.74$, $p < .0001$). The backrest display also showed a higher likelihood of MS than the armrest display (OR = 1.58, 95% CI [1.03, 2.44], $\chi^2(1) = 9.72$, $p = .027$). Under the unblocked view condition, the roof display was again associated with a lower likelihood of MS than the backrest display (OR = 0.57, 95% CI [0.34, 0.96], $\chi^2(1) = 9.96$, $p = .024$). When comparing view conditions within the same display, the blocked view condition was associated with a higher likelihood of MS than the unblocked view condition for all display locations, including the roof display (OR = 1.65, 95% CI [1.01, 2.71], $\chi^2(1) = 8.43$, $p = .04$), the backrest display (OR = 4.11, 95% CI [2.57, 6.57], $\chi^2(1) = 78.03$, $p < .0001$) and the armrest display (OR = 3.26, 95% CI [2.03, 5.25], $\chi^2(1) = 53.57$, $p < .0001$).



(a) (b)

Figure 10. The interaction effects in the M2 model: a) between view condition and display location; b) between time and display location.

Further, As shown in Figure 10b, for the interaction between time and the display location, the roof display was associated with a slightly slower increase in the likelihood of experiencing moderate or higher MS (MISC ⩾ 4) compared with the backrest display (OR = 0.97, 95% CI [0.94, 0.99], $\chi^2(1) = 9.43$, $p = .006$) for each additional minute.

5.4.3 M3 Model with MISC Threshold of 6

For M3, three interaction effects were observed, i.e., between display location and view condition, between display location and time, and between view condition and time. Specifically, for the interaction between view condition and time, the time effect was significantly greater in the blocked view condition than in the unblocked view condition, with an OR of 1.11, 95% confidence interval (95% CI): [1.06, 1.16], $\chi^2(1) = 21.54$, $p < 0.0001$ (see Figure 11a).

At the same time, as shown in Figure 11b, a significant effect of display location on the time trend was observed. Specifically, the roof display was associated with a slightly slower increase in the likelihood of experiencing severe or higher MS (MISC ⩾ 6) compared with the armrest display (OR = 0.93, 95% CI [0.87, 0.99], $\chi^2(1) = 6.40$, $p = .031$) for each additional minute. In addition, the backrest display also showed a slower increase in the likelihood of MS compared with the armrest display (OR = 0.89, 95% CI [0.84, 0.94], $\chi^2(1) = 21.96$, $p < .001$).

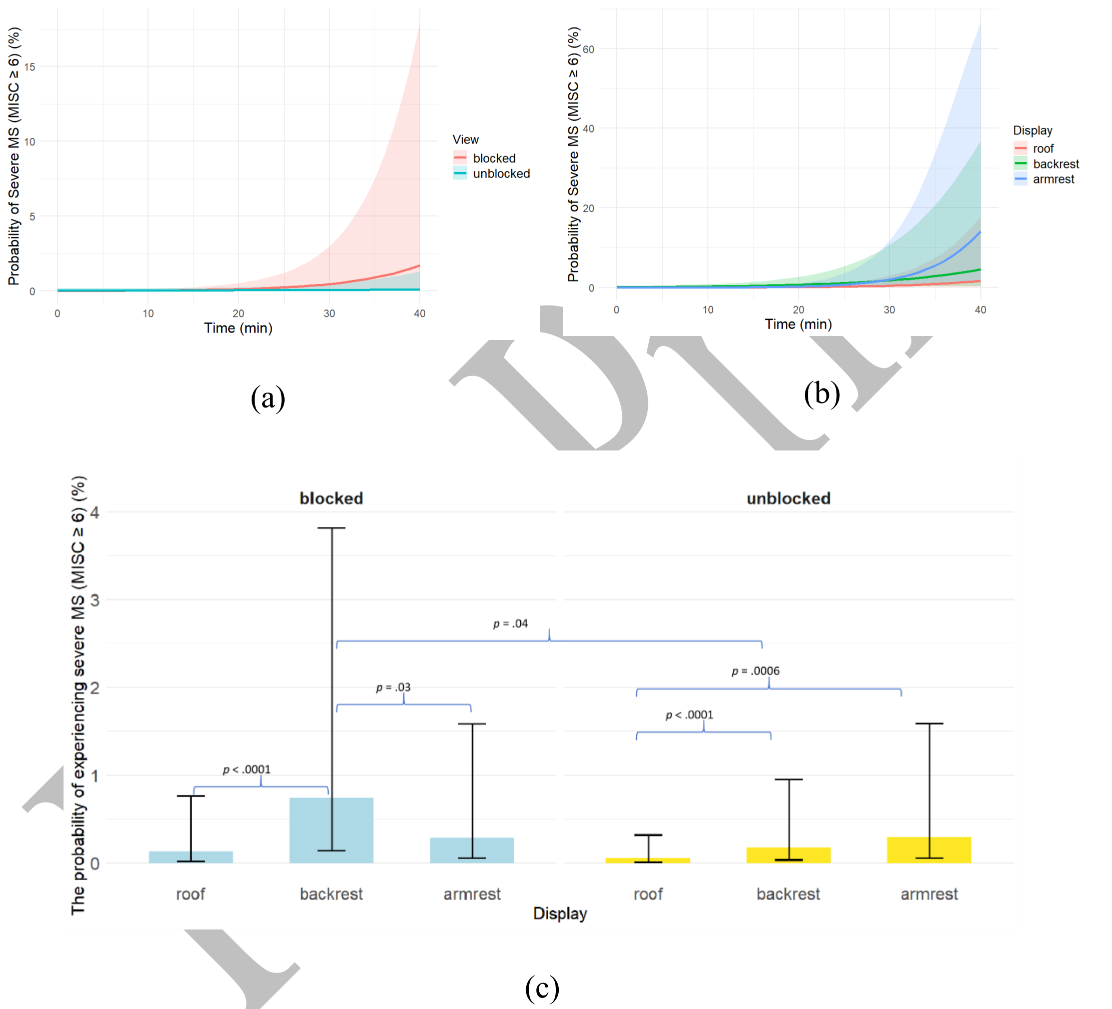


Figure 11. The interaction effects in the M3 model: a) between view condition and time; b) between display location and time; c) between view condition and display location.

Further, as shown in Figure 11c, for the interaction between display location and view condition, under the blocked view condition, the roof display was associated with a substantially lower likelihood of experiencing severe or higher MS (MISC $\geqslant 6$) compared with the backrest display (OR = 0.18, 95% CI [0.09, 0.38], $\chi^2(1) = 23.42$, $p < .0001$). In the same view condition, the backrest display was also associated with a higher likelihood of MS than the armrest display (OR = 2.58, 95% CI [1.09, 6.10], $\chi^2(1) = 9.07$, $p = .031$). At the same time, under the unblocked view condition, the roof display was associated with a lower likelihood of MS compared with both the backrest display (OR = 0.31, 95% CI [0.12, 0.83], $\chi^2(1) = 8.52$, $p = .04$) and the armrest display (OR = 0.18, 95% CI [0.07, 0.44], $\chi^2(1) = 16.86$, $p = .0001$). When comparing view conditions for the same display, the blocked view was associated with a higher likelihood of MS than the unblocked view for both the backrest display (OR = 4.29, 95% CI [2.38, 7.73], $\chi^2(1) = 23.75$, $p < .001$) and the armrest display (OR = 5.43, 95% CI [1.71, 17.23], $\chi^2(1) = 13.16$, $p = .004$).

6. Discussion

In this study, we reveal how a seemingly simple design choice, i.e., the display position in the cabin, can affect passengers' MS in smart cabins by shaping perceptual and head postural constraints. Specifically, the display location, as an interface design variable, can shape both peripheral visual access and head posture, which in turn may modulate sensory conflict and influence the development of MS.

6.1 Key Findings

In response to RQ1, the results of all three models consistently indicated that the roof display may be more preferred for mitigating MS under both viewing conditions, than the backrest and arrest display. This conclusion is supported by the significant interaction effect between display location and view condition observed across the three models. Specifically, under the unblocked-view condition, the roof display outperformed the backrest and armrest displays in all three models: 1) in the M1 model (MISC $\geqslant$ 2; see Figure 9c), it was associated with a lower MS level than both the backrest display and the armrest display; 2) in the M2 model (MISC $\geqslant$ 4; see Figure 10a), it again outperformed the backrest display, and 3) in the M3 model (MISC $\geqslant$ 6; see Figure 11c), it was associated with a lower MS level than both the backrest and armrest displays.

Similarly, under the blocked-view condition, the roof display consistently outperformed the other locations: 1) in the M1 model (MISC $\geqslant$ 2; see Figure 9c), it was associated with a lower MS than both the backrest and armrest displays; 2) in the M2 model (MISC $\geqslant$ 4; see Figure 10a), it was associated with a lower MS than both the backrest and armrest displays; and 3) in the M3 model (MISC $\geqslant$ 6; see Figure 11c), it was again associated with a lower MS than the backrest display.

Furthermore, the significant interaction between display position and time further suggests an advantage of the roof display. In the M1 model, MS increased more slowly with the roof display than with the backrest and armrest displays. Consistent patterns were observed in the M2 and M3 models, in which the roof display again exhibited a slower rate of MS increase than the backrest and armrest displays, respectively. Taken together, these results indicate that the roof display was consistently associated with a slower MS development than both the backrest and armrest displays in our experiment, regardless of external-view availability.

To address RQ2, we further examined the interaction effects between display location and view condition. As expected, the availability of the external view was associated with the temporal development of MS. Specifically, the unblocked-view condition was associated with a slower increase in MS, as evidenced by the significant interaction between view condition and time in both the M1 (Figure 9a) and M3 (Figure 11a) models. Furthermore, across models, the unblocked condition was generally associated with a lower MS level than the blocked condition for the roof display in the M1 and M2 models, for the backrest display in all three models (M1–M3), and for the armrest display in the M1 and M2 models. This finding is consistent with previous research (Xie, He, et al., 2023) and theoretically reasonable: when passengers have access to an external view, they can better perceive road motion, remain aware of the vehicle's current dynamics, and anticipate upcoming movements (Rolnick & Lubow, 1991)—all of which help mitigate sensory conflict and reduce MS.

Finally, it should be noted that the benefit of the unblocked view was most consistent for the backrest display, whereas it was only partially effective for the roof and armrest displays. This pattern is understandable: the armrest display inherently restricts passengers' ability to perceive the outside environment, forcing them to maintain a downward head posture even when the external view is available. In contrast, the backrest display allows passengers to maintain a more natural, forward-facing posture, thereby facilitating the integration of visual motion cues under the unblocked condition. The absence of a significant difference for the roof display and armrest display in the M3 model (MISC $\geqslant$ 6) may be attributed to the limited number of participants who reached severe motion sickness levels under the blocked-view condition, reducing the statistical power to detect an effect.

6.2 Mechanisms behind Findings: Visual Motion Perception and Head Posture

The observed advantages of the roof display may be interpreted through two complementary interaction mechanisms: peripheral visual motion perception and head posture–related motion dynamics. First, display location determines the extent to which passengers can access peripheral visual motion cues from the external environment while interacting with in-vehicle systems. When the external view was available, the roof display allowed passengers to maintain a more forward-facing visual orientation, thereby facilitating better integration of road-motion information and more accurate anticipation of vehicle dynamics. This interpretation is consistent with the significant interaction effects between display location and view condition observed across models.

Second, display placement implicitly constrains head posture, which in turn influences head-fixed motion dynamics relevant to vestibular conflict. Compared with the backrest and armrest displays, the roof display encouraged a more upright and forward-facing head orientation, whereas the armrest display required a sustained downward gaze. Such differences in head posture may alter the motion stimuli to which the head is exposed, thereby modulating sensory conflict. The continued advantage of the roof display under blocked-view conditions supports this interpretation, suggesting that factors beyond visual accessibility, specifically head posture and head-motion patterns, contribute to MS mitigation. Such a pathway indicates that, in contrast to previous research, which claims that differences in motion sickness across display positions can be fully explained by the availability of a road view (Kuiper et al., 2018), factors beyond visual accessibility, such as head posture and the resulting motion dynamics, may contribute to the observed differences across display locations in terms of MS development.

In addition to the proposed pathways, alternative explanatory mechanisms should be considered. Differences in attention allocation, cognitive workload, and motion expectation may also influence MS. In the present study, the video-watching task was the only entertainment task allowed, and task accuracy did not differ significantly across conditions, suggesting that task-induced cognitive load and engagement were broadly comparable. In addition, video clips and display–view combinations were counterbalanced using a Latin square design, which helps minimize systematic order or content-related confounds. However, these controls cannot fully rule out more subtle differences in gaze distribution or expectancy across display locations. Display placement may influence how attention is divided between the display and the environment, which in turn may shape motion anticipation and symptom development. Future studies incorporating direct measurements of gaze behavior, pupil-based workload, or subjective workload ratings would help disentangle these complementary pathways.

6.4 Implications for In-Vehicle Interaction Design

From an HCI perspective, these findings highlight display location as a critical interface design variable, as placement can simultaneously shape users' access to peripheral visual motion cues and head posture constraints during NDRTs on the display. Thus, the results suggest that rear-seat interface designs may benefit from display configurations that preserve peripheral awareness of vehicle motion and minimize unfavorable head postures from an MS mitigation perspective. In particular, roof-mounted displays may represent a promising design option for rear-seat smart cabins, as they support both visual motion perception and ergonomically favorable head orientations, though this conclusion should be interpreted within the boundaries of the present sample and setting, given that participants in our study were young adults with high motion-sickness susceptibility, tested in a single vehicle type, on one urban route, and in a fixed right-rear seating position.

6.5 Comparison with Prior Work

Previous research has demonstrated that display placement can influence MS, particularly when comparing head-up and head-down displays in driver-centered or front-seat contexts (Bos & Bles, 1998; Kuiper et al., 2018). These studies largely attribute MS differences to variations in visual access to the road environment. Our findings extend this line of research in two important ways. First, we found that the display location effects may persist in rear-seat contexts when passengers engage in sustained visual NDRTs on the display. Further, we found that the display location may continue to matter even when the external view is fully blocked, suggesting that head posture–related mechanisms play an additional role beyond visual accessibility alone. This interpretation is consistent with prior modeling and simulation work, which proposed that head-fixed motion dynamics contribute to MS development (Xie, Yan, et al., 2023); our current study appears to support this mechanism by providing empirical evidence on the road.

6.6. Integrated Limitations

There are several limitations of our work. First, although we adopted a within-subject design to eliminate the individual differences, only 24 participants took part in the study, and they were required to have a high susceptibility to MS. Given that MS inducers may have different effects on individuals with different levels of MSSQ (Hainich et al., 2021; Li et al., 2023), the readers should be cautious when applying our conclusions to a larger population.

Further, to capture the progressive nature of MS, we employed multiple mixed-effects and logistic regression models at different MISC thresholds (⩾2, ⩾4, ⩾6), each representing a distinct level of symptom severity. These analyses were intended to identify potential patterns and threshold-specific effects rather than to draw confirmatory conclusions. In particular, we adopted a forward-filling strategy to address early ride discontinuation, which may overestimate late-stage symptom severity by treating all post-discontinuation time points as equally severe and by failing to capture potential habituation or recovery effects. Moreover, relatively few participants reached severe MS levels. Consequently, estimates from the M3 model (MISC $\geq$ 6) are based on a small number of severe cases and should be interpreted with caution. Accordingly, the present study provides exploratory insights into how display location and view condition jointly influence the onset and progression of MS.

Additionally, in our experiment, all participants sat in the rear seat, and the experiment was conducted on selected urban roads that are mostly flat and feature smooth curves. Therefore, our conclusions may not be generalizable to front-seat passengers, given differences in vehicle vibration (Rikaz et al., 2019) and viewing conditions (Salter et al., 2019) across seats, and may not be generalizable to all typical road environments.

Next, a key limitation of the present study is the confounding of multiple interface design dimensions within each display location. The three display configurations differed simultaneously in vertical position, viewing angle, viewing distance, and screen orientation. Consequently, the current experimental design does not permit isolation of the independent contribution of individual design parameters (e.g., height, inclination, or viewing distance) to MS outcomes. Further, although the video clips and display–view combinations were counterbalanced using a Latin square design, which should have helped minimize systematic order or content-related confounds, these controls may still not fully rule out more subtle differences in gaze distribution or expectancy across display locations.

7. Conclusions

In this study, we conducted an on-road experiment to compare the effects of display locations on MS and to examine why these locations matter. We found:

- First, the external-view condition was associated with a lower MS level than the view-blocked condition, consistent with prior studies indicating that visual access to the road reduces sensory conflict and improves ride comfort (Xie, He, et al., 2023).
- Second, when passengers had full access to the external road view, the roof display was associated with the lowest MS levels, suggesting it may be a promising location for reducing MS. Inspired by previous studies that highlighted the role of motion cues in mitigating MS (Bohrmann et al., 2022), we argued that this may be because the roof display allowed passengers to maintain road visibility and situational awareness better, thereby enabling more accurate anticipation of upcoming vehicle motion.
- Third, even when the external view was fully blocked, the roof display tended to be more effective than other display locations in reducing MS. Again, inspired by previous simulation studies (Xie, Yan, et al., 2023), we assume that

this advantage may be attributed to the head posture and head-motion patterns induced by the roof display, which appeared to reduce sensory conflict.

Taken together, these findings contribute to an interaction-aware perspective on in-vehicle interface design. We suggest that effective MS mitigation cannot rely solely on the content or modality of motion cues (e.g., Hainich et al., 2021), but should also consider how interface placement constrains visual access and head posture during interaction. From a design standpoint, display configurations that preserve peripheral awareness of vehicle motion and support ergonomically favorable head orientations, such as roof-mounted displays, may offer a promising direction for rear-seat smart cabin interfaces. More broadly, this work suggests a design paradigm in which motion perception, head posture, and interaction can be thoroughly considered to improve in-vehicle user experience.

However, it should be noted that the present findings should be interpreted within the scope of the current experimental context. The study was conducted with a young, motion-susceptible sample who sat at a fixed right-rear seating position, on a single urban driving route. Accordingly, the results are most directly applicable to comparable rear-seat interaction scenarios, particularly video-watching tasks involving fixed display positions in similar smart-cabin environments.

While the observed patterns provide initial empirical support for the role of display placement in shaping motion perception and MS development, further research across broader populations, vehicle types, and interaction contexts is needed to assess the generalizability of findings with different road profiles (e.g., on steep roads, windy roads, and long straight highways). Future research can also adopt factorial or parametric designs that independently manipulate display height, inclination, and viewing distance to disentangle their individual and interactive contributions to MS. Further analytical approaches can also be considered, such as survival-based models (Ohno-Machado, 2001) and joint modeling of symptom progression and dropout (Saulnier et al., 2022) to handle early ride discontinuation, though the forward-filling strategy we adopted has provided a preliminary estimation of the display location effects.

Author contributions

CRediT: Weiyin Xie: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing; Zhenyu Wang: Data curation, Formal analysis; Yulu Jiang: Data curation; Chunxi Huang: Formal analysis; Jiyao Wang: Formal analysis, Methodology; Dengbo He: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing

Declaration of Competing Interest

The authors acknowledge that they have no conflicts of interest in this work.

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REFERENCES

Bates, D. M. (2010). lme4: Mixed-effects modeling with R. In: Springer.

Bohrmann, D., Bruder, A., & Bengler, K. (2022). Effects of dynamic visual stimuli on the development of carsickness in real driving. *IEEE Transactions on Intelligent Transportation Systems*, *23*(5), 4833-4842.

Bolker, B. (2019). Getting started with the glmmTMB package. *Cran. R-project vignette*, *9*.

Bos, J., & Bles, W. (1998). Modelling motion sickness and subjective vertical mismatch detailed for vertical motions. *Brain research bulletin*, *47*(5), 537-542.

Bos, J. E., MacKinnon, S. N., & Patterson, A. (2005). Motion sickness symptoms in a ship motion simulator: effects of inside, outside, and no view. *Aviation, space, and environmental medicine*, *76*(12), 1111-1118.

Cho, H.-J., & Kim, G. J. (2022). RideVR: reducing sickness for in-car virtual reality by mixed-in presentation of motion flow information. *IEEE Access*, *10*, 34003-34011.

Cristovao, N. (2021). *Everything we know about the Tesla Model S and Model X redesign.* Not a Tesla App. Retrieved April from https://www.notateslaapp.com/news/65/everything-we-know-about-the-tesla-model-s-and-model-x-redesign

Diels, C., & Bos, J. E. (2016). Self-driving carsickness. *Applied Ergonomics*, *53*, 374-382.

Donohew, B. E., & Griffin, M. J. (2004). Motion sickness: effect of the frequency of lateral oscillation. *Aviation, space, and environmental medicine*, *75*(8), 649-656.

Faurecia. (2023). *FORVIA and Chery join forces for smart cockpit development.* FORVIA. https://www.faurecia.com/en/newsroom/forvia-and-chery-join-forces-smart-cockpit-development

Golding, J. F. (2006). Predicting individual differences in motion sickness susceptibility by questionnaire. *Personality and Individual differences*, *41*(2), 237-248.

Golding, J. F., Bles, W., Bos, J., Haynes, T., & Gresty, M. A. (2003). Motion sickness and tilts of the inertial force environment: active suspension systems vs. active passengers. *Aviation, space, and environmental medicine*, *74*(3), 220-227.

Hada, H. (1994). *DRIVERS'VISUAL ATTENTION TO IN-VEHICLE DISPLAYS: EFFECTS OF DISPLAY LOCATION AND ROAD TYPES.*

Hainich, R., Drewitz, U., Ihme, K., Lauermann, J., Niedling, M., & Oehl, M. (2021). Evaluation of a human–machine interface for motion sickness mitigation utilizing anticipatory ambient light cues in a realistic automated driving setting. *Information*, *12*(4), 176.

Irmak, T., Pool, D. M., & Happee, R. (2021). Objective and subjective responses to motion sickness: the group and the individual. *Experimental Brain Research*, *239*(2), 515-531.

ISO2631-1. (1997). Mechanical vibration and shock: Evaluation of human exposure to whole-body vibration—Part 1: General requirements (ISO Standard No. 2631-1). In: International Organization for Standardization.

ISO8855. (2011). Road vehicles—Vehicle dynamics and road-holding ability—Vocabulary (ISO Standard No. 8855:2011). In: International Organization for Standardization.

Isu, N., Hasegawa, T., Takeuchi, I., & Morimoto, A. (2014). Quantitative analysis of time-course development of motion sickness caused by in-vehicle video watching. *Displays*, *35*(2), 90-97.

Kamiji, N., Kurata, Y., Wada, T., & Doi, S. i. (2007). Modeling and validation of carsickness mechanism. SICE Annual Conference 2007,

Kang, H. (2021). Sample size determination and power analysis using the G* Power software. *Journal of educational evaluation for health professions*, *18*.

Karjanto, J., Yusof, N. M., Wang, C., Terken, J., Delbressine, F., & Rauterberg, M. (2018). The effect of peripheral visual feedforward system in enhancing situation awareness and mitigating motion sickness in fully automated driving. *Transportation research part F: traffic psychology and behaviour*, *58*, 678-692.

Kato, K., & Kitazaki, S. (2006). A study of carsickness of rear-seat passengers due to acceleration and deceleration when watching an in-vehicle display. *Review of automotive engineering*, *27*(3), 465.

Kuiper, O. X., Bos, J. E., & Diels, C. (2018). Looking forward: In-vehicle auxiliary display positioning affects carsickness. *Applied Ergonomics*, *68*, 169-175.

Kuiper, O. X., Bos, J. E., Schmidt, E. A., Diels, C., & Wolter, S. (2020). Knowing what's coming: unpredictable motion causes more motion sickness. *Human factors*, *62*(8), 1339-1348.

Lam, J. (2018). *The New Rolls-Royce Privacy Suite uses electrochromatic glass*. Trendhunter. Retrieved Feburary from https://www.trendhunter.com/trends/rollsroyce-privacy-suite

Lawther, A., & Griffin, M. (1986). The motion of a ship at sea and the consequent motion sickness amongst passengers. *Ergonomics*, *29*(4), 535-552.

Lenth, R. (2022). emmeans: Estimated marginal means, aka least-squares means. R package version 1.7. 2. In.

Li Auto. (2022). *Li Auto Inc. unveils Li L9, its flagship smart SUV.* Retrieved April from https://ir.lixiang.com/news-releases/news-release-details/li-auto-inc-unveils-li-l9-its-flagship-smart-suv/

Li, D., Xu, B., Chen, L., Tang, B., Yu, T., Zhou, K., Qie, N., Shi, Y., Lu, C., & Zhang, H. (2023). Mosi app-a motion cueing application to mitigate car sickness while performing non-driving task. International Conference on Human-Computer Interaction,

Lim, H. K., Ji, K., Woo, Y. S., Han, D.-u., Lee, D.-H., Nam, S. G., & Jang, K.-M. (2021). Test-retest reliability of the virtual reality sickness evaluation using electroencephalography (EEG). *Neuroscience Letters*, *743*, 135589.

Lin, Y., & Guo, G. (2022). *Research on the evaluation and relief with olfaction method of passengers carsickness degree* [master's thesis, Chongqing University].

Lohse, K. R., Kozlowski, A. J., & Strube, M. J. (2022). Model specification in mixed-effects models: a focus on random effects. *arXiv preprint arXiv:2209.14349*.

Maculewicz, J., Larsson, P., & Fagerlönn, J. (2021). Intuitive and subtle motion-anticipatory auditory cues reduce motion sickness in self-driving cars. *International journal of human factors and ergonomics*, *8*(4), 370-392.

MarketsandMarkets. (2023). *In-vehicle infotainment market size, share, forecast, report, 2030.* MarketsandMarkets. https://www.marketsandmarkets.com/Market-Reports/in-car-vehicle-infotainment-ici-systems-market-538.html

Meschtscherjakov, A., Strumegger, S., & Trösterer, S. (2019). Bubble margin: Motion sickness prevention while reading on smartphones in vehicles. Human-Computer Interaction–INTERACT 2019: 17th IFIP TC 13 International Conference, Paphos, Cyprus, September 2–6, 2019, Proceedings, Part II 17,

MotorTrend. (2023). *The best SUVs with TVs: rear-seat entertainment with space to stretch out.* . MotorTrend. https://www.motortrend.com/features/suvs-with-tvs/

Ohno-Machado, L. (2001). Modeling medical prognosis: survival analysis techniques. *Journal of biomedical informatics*, *34*(6), 428-439.

Qiu, Z., McGill, M., Pöhlmann, K. M. T., & Brewster, S. A. (2022). Display rotation for reducing motion sickness caused by using VR in vehicles. Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications,

Reason, J. T. (1978). Motion sickness adaptation: a neural mismatch model. *Journal of the royal society of medicine*, *71*(11), 819-829.

Rempel, D., Willms, K., Anshel, J., Jaschinski, W., & Sheedy, J. (2007). The effects of visual display distance on eye accommodation, head posture, and vision and neck symptoms. *Human factors*, *49*(5), 830-838.

Rikaz, M., Abeysinghe, A., & Perera, M. (2019). Review on vibration quality improvement of a passenger seat. *Vibroengineering Procedia*, *22*, 106-111.

Rolnick, A., & Lubow, R. (1991). Why is the driver rarely motion sick? The role of controllability in motion sickness. *Ergonomics*, *34*(7), 867-879.

Salter, S., Diels, C., Herriotts, P., Kanarachos, S., & Thake, D. (2019). Motion sickness in automated vehicles with forward and rearward facing seating orientations. *Applied Ergonomics*, *78*, 54-61.

Sato, H., Sato, Y., Takamatsu, A., Makita, M., & Wada, T. (2022). Earth-fixed books reduce motion sickness when reading with a head-mounted display. *Frontiers in Virtual Reality*, *3*, 909005.

Saulnier, T., Philipps, V., Meissner, W. G., Rascol, O., Pavy-Le Traon, A., Foubert-Samier, A., & Proust-Lima, C. (2022). Joint models for the longitudinal analysis of measurement scales in the presence of informative dropout. *Methods*, *203*, 142-151.

Schmidt, E. A., Kuiper, O. X., Wolter, S., Diels, C., & Bos, J. E. (2020). An international survey on the incidence and modulating factors of carsickness. *Transportation research part F: traffic psychology and behaviour*, *71*, 76-87.

Smyth, J., Robinson, J., Burridge, R., Jennings, P., & Woodman, R. (2021). Towards the management and mitigation of motion sickness–an update to the field. Congress of the International Ergonomics Association,

Sugiura, T., Wada, T., Nagata, T., Sakai, K., & Sato, Y. (2019). Analysing effect of vehicle lean using cybernetic model of motion sickness. *IFAC-PapersOnLine*, *52*(19), 311-316.

Suwa, T., Sato, Y., & Wada, T. (2022). Reducing motion sickness when reading with head-mounted displays by using see-through background images. *Frontiers in Virtual Reality*, *3*, 910434.

Suzuki, H., Shiroto, H., & Tezuka, K. (2005). Effects of low frequency vibration on train motion sickness. *Quarterly Report of RTRI*, *46*(1), 35-39.

Turner, M., Griffin, M. J., & Holland, I. (2000). Airsickness and aircraft motion during short-haul flights. *Aviation, space, and environmental medicine*, *71*(12), 1181-1189.

Wada, T., Konno, H., Fujisawa, S., & Doi, S. i. (2012). Can passengers' active head tilt decrease the severity of carsickness? effect of head tilt on severity of motion sickness in a lateral acceleration environment. *Human factors*, *54*(2), 226-234.

Wada, T., & Yoshida, K. (2016). Effect of passengers' active head tilt and opening/closure of eyes on motion sickness in lateral acceleration environment of cars. *Ergonomics*, *59*(8), 1050-1059.

Xie, W., He, D., & Wu, G. (2023). Inducers of motion sickness in vehicles: a systematic review of experimental evidence and meta-analysis. *Transportation research part F: traffic psychology and behaviour*, *99*, 167-188.

Xie, W., Huang, C., Yan, S., & He, D. (2024). Do electric vehicles induce more motion sickness than fuel vehicles? A survey study in China. Transport Research Board, Washington, U.S.

Xie, W., Yan, S., Huang, C., & He, D. (2023). The influence of display location on motion sickness: an analysis based on 6-DoF SVC model. Adjunct Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, YueXiAn. (2023). *The 2023 Commuting Monitoring Report of Major Cities in China.* https://www.sohu.com/a/www.sohu.com/a/714221358_735537

Yunus, I., Jerrelind, J., & Drugge, L. (2021). Evaluation of motion sickness prediction models for autonomous driving. The IAVSD International Symposium on Dynamics of Vehicles on Roads and Tracks,

Appendix

Figure A.1 illustrates the progression of MISC scores over time for each participant under all experimental conditions.

Figure A.1. Progression of MISC scores over time for each participant

The time-series plots of average angular velocity across experimental conditions are shown in Figure A.2.

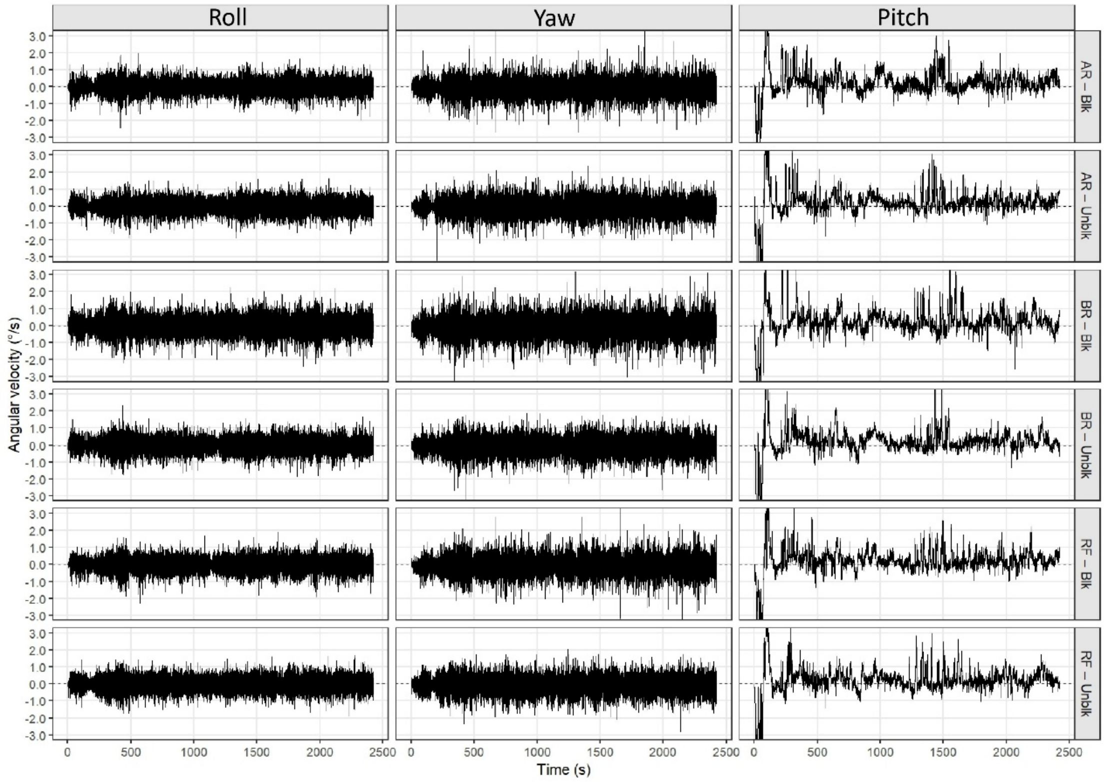

Figure A.2. Time-series plots of average roll, yaw, and pitch by experimental conditions (AR: armrest; BR: backrest; RF: roof; Blk: blocked; Unblk: unblocked).

The time-series plots of lateral, longitudinal, and vertical accelerations for each experimental condition are presented in Figure A.3.

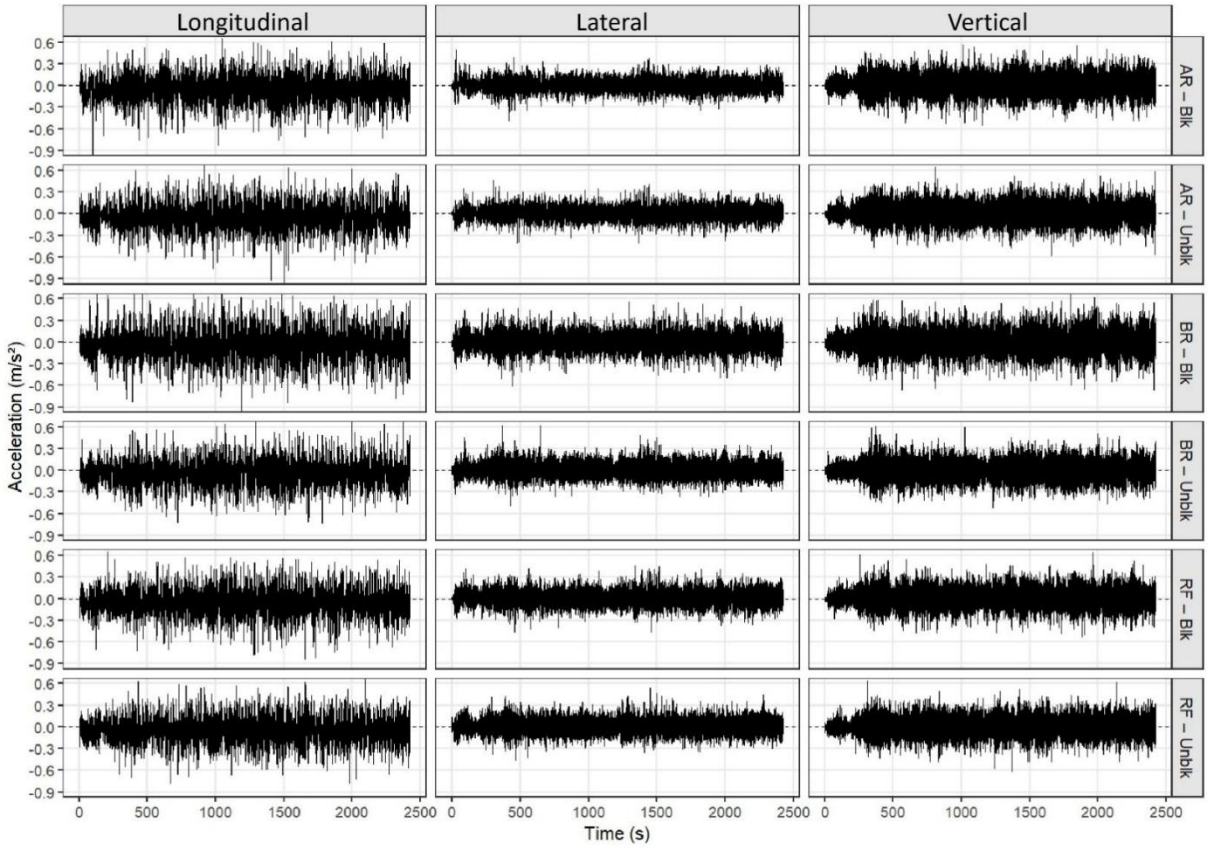

Figure A. 3 Time-series plots of linear acceleration by experimental condition (AR: armrest; BR: backrest; RF: roof; Blk: blocked; Unblk: unblocked).

The boxplot of mean journey speed for each experimental condition is presented in Figure A.4. Further ANOVA analyses revealed no significant differences in mean speed across view conditions and display locations (*p* > .05).

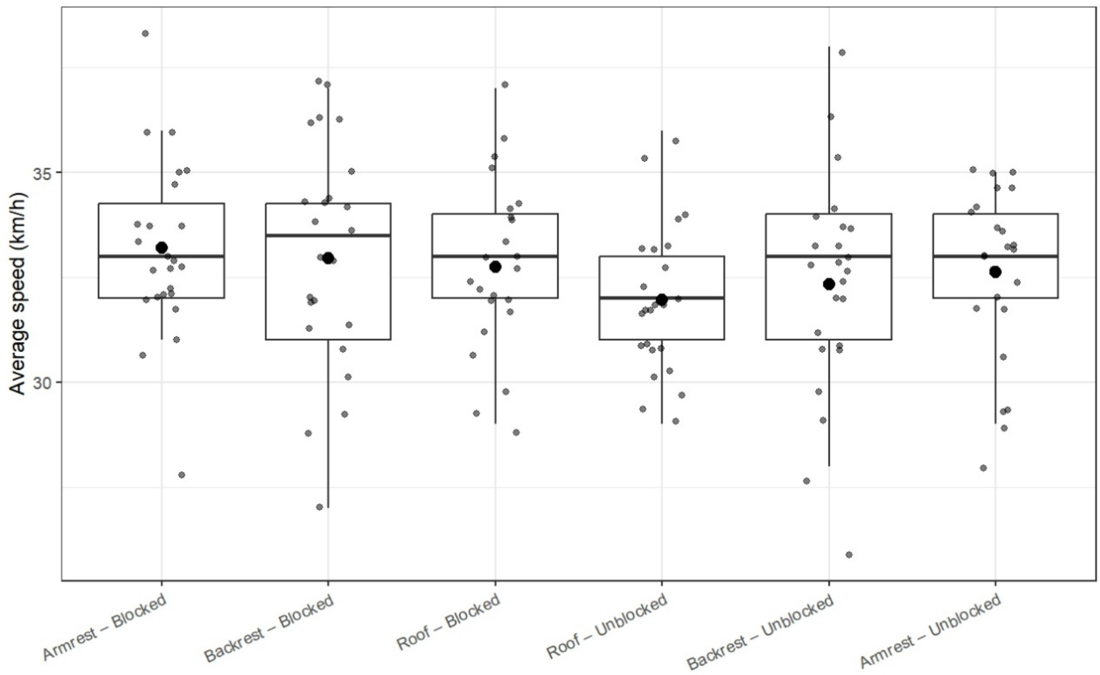

Figure A. 4 Distribution of mean acceleration across experimental conditions.

In addition, to evaluate potential differences in driving aggressiveness, we quantified the occurrence of rapid acceleration and deceleration events using predefined longitudinal and lateral acceleration thresholds. Specifically, the thresholds for absolute longitudinal and lateral acceleration were set at 1.89 m/s^2 and 1.65 m/s^2, respectively, based on passenger discomfort thresholds reported in previous studies[1]. For each journey and experimental condition, the number of data points exceeding these

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[1] De Winkel, K. N., Irmak, T., Happee, R., & Shyrokau, B. (2023). Standards for passenger comfort in automated vehicles: Acceleration and jerk. *Applied Ergonomics*, *106*, 103881.

thresholds was visualized in Figure A.5. Further negative binomial regression test revealed no significant differences across experimental conditions in the number of aggressive acceleration and deceleration events.

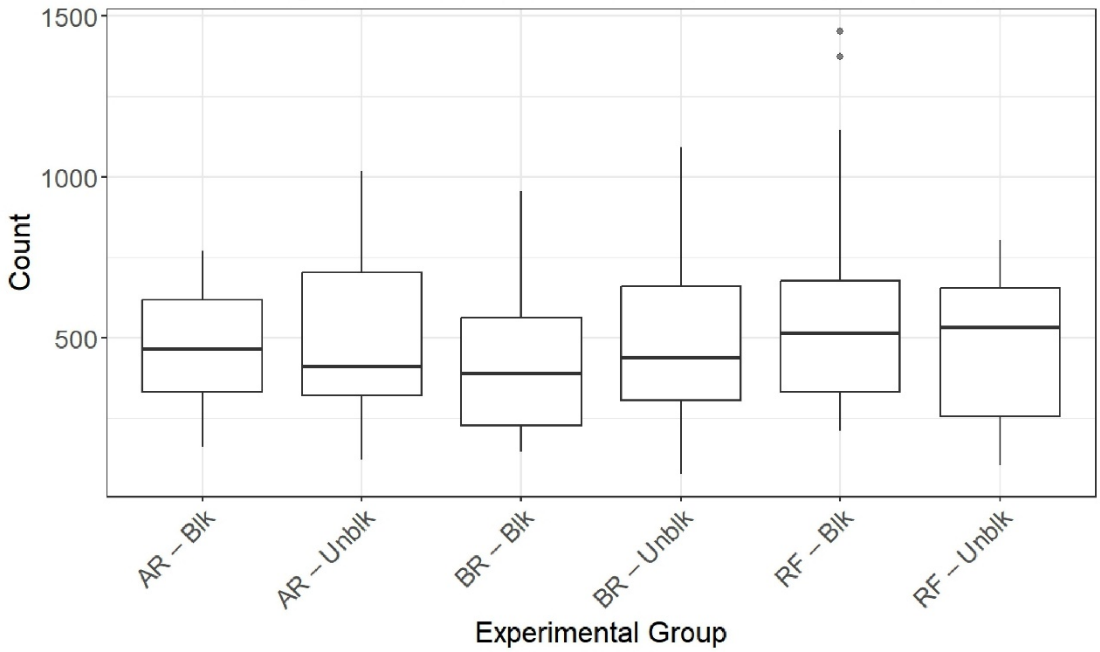

Figure A. 5 Distribution of data points exceeding acceleration thresholds per journey across conditions (AR: armrest; BR: backrest; RF: roof; Blk: blocked; Unblk: unblocked)

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