The Influence of Display Location on Motion Sickness: An Analysis Based on 6-DoF SVC Model

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With the prevalence of smart cockpits, passengers spend increasingly more time engaging with non-driving related tasks (NDRTs, e.g., in-vehicle entertainment and meetings) in vehicles. However, prolonged NDRT engagement can cause sensory conflict and result in motion sickness. Previous research found that motion sickness is highly associated with head motion, which can further be influenced by the positions of the NDRT displays. To guide the design of the smart cockpit, this paper examines the impact of four common NDRT display locations on passengers' motion sickness. A motion transfer function was utilized to translate a real-world vehicle trajectory into head motion when passengers looked at displays at different locations. Then, a 6 Degree-of-Freedom subjective vertical conflict model was adopted to evaluate the motion sickness caused by head motion. The results of this study can inform the design of in-vehicle displays and improve passenger comfort.

CCS CONCEPTS • Human-centered computing •Visualization • Visualization design and evaluation methods

Additional Keywords and Phrases: Motion Sickness, In-vehicle HMI, Display Location, Vehicle Dynamics

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1 Introduction

The in-vehicle infotainment systems (IVISs) have been widely adopted in vehicles in recent years and some automobile manufacturers even incorporate IVISs as a standard feature [6]. The IVIS can fulfill several functions, such as navigation, entertainment, climate control, and safety alerts. It is estimated that the automotive smart display market will be valued at USD 10.9 billion by 2025 [12]. Even without IVIS, drivers and passengers are inclined to use bring-in electronic devices (such as cellphones and tablets) in vehicles, for both entertainment and work. The increasing time spent on screens in vehicles has raised the concern about motion sickness in vehicles.

Motion sickness is a common and uncomfortable condition characterized by symptoms such as nausea, dizziness, and vomiting [20]. According to a survey study, 59% out of 4479 respondents have experienced in-vehicle motion sickness (i.e., car sickness) at some point in their lives [19]. Despite advances in IVIS in recent years, motion sickness remains a major obstacle to the application of smart cockpit, as the risk of experiencing motion sickness can be increased by watching videos in a moving vehicle [19] [14] [7].

Several theories might explain the causes of motion sickness. For example, according to the sensory conflict theory, motion sickness occurs when the visual motion cues are inconsistent with the ego-motion perceived by the vestibular system [17]. In vehicles, when passengers look at the in-vehicle displays, their visual system would perceive the environment as static, while their vestibular system detects the acceleration of the vehicle – this sensory conflict can increase the chance of motion sickness in vehicles. Thus, providing motion cues of the ego-vehicle may reduce the likelihood of motion sickness in vehicles [8] as this would enhance passengers' ability to perceive and predict the motion of their body. The effectiveness of utilizing a virtual reality (VR) display to reduce motion sickness has been explored in previous research studies. For example, [16] rotated the motion cues in synchrony with the physical motion that the subjects experience in the VR display and successfully reduced the symptoms associated with motion sickness among passengers. In another study, motion information of the ego vehicle was delivered through the bubbles cues on the margins of a smartphone, resulting in a notable alleviation of motion sickness symptoms [13].

In addition to the provision of artificial motion cues, improved visibility of the road was also found to alleviate motion sickness [1], given that the enhanced visibility of the road improves the perception of the ego vehicle's motion, thereby reducing the likelihood of experiencing motion sickness. Thus, the display location that would facilitate drivers' perception of the vehicle's motion should be able to reduce motion sickness as well. It was found that the head-up display (near the windshield) was less likely to lead to motion sickness compared to the head-down display (near the glove compartment) [10], potentially because the drivers can perceive more motion information with the head-up display.

However, sensory conflict is not the only factor that could influence motion sickness in vehicles. Several works of literature pointed out that head motion may also be associated with the level of motion sickness [9]. Furthermore, the alignment of the head with the gravity-inertial force (GIF) [4] and head tilting during cornering [22] were also found to have an impact on motion sickness. Thus, the NDRT display may influence motion sickness, not only from the sensory conflict perspective of view but also from the head motion perspective of view, as the location of the display influences the rotation angle of the head relative to the body, consequently affecting the characteristics of head motion and vibration. However, previous studies were not unable to distinguish between the effects of sensory conflict and head motion on the induction of motion sickness in vehicles when considering the influence of the display location. Further, the smart cockpits in recent vehicle models deployed NDRT displays at different locations, but no research has investigated users' susceptibility to motion sickness when using these displays.

Thus, to better understand how the display location can influence motion sickness in vehicles, we aimed to: 1) evaluate the level of motion sickness induction of displays at several common locations; 2) differentiate the effects of sensory conflict and head motion on the induction of motion sickness. To do so, several on-road studies are needed. As an ongoing preliminary work, in this paper, we report a preliminary analysis of how display location may affect head motion and thus influence the vestibular-related motion sickness level. Based on a motion transfer function (from the vehicle body to the head) and 6 degrees-of-freedom (DoF) subjective vertical conflict (SVC) model [21], we calculated the vestibular-related motion sickness levels of rear-seat passengers resulting from looking at NDRT displays at four different locations.

2 Method

As shown in Figure 1, using a within subject experiment design, we first measured the head poses when the passenger looked at the displays at four locations in vehicles in static. The display locations were selected based on a thorough review of the interior design of mainstream passenger vehicles. The locations include (see Figure 1): (1) a display mounted on the backrest of the front row seats, placed at eye level for right rear passengers (i.e., headrest screen, Ford Expedition [23]); (2) a display mounted on the lower part of the backrest of the front row seats, requiring right rear passengers to look downward to view the screen (i.e., backrest screen, BMW 5 series [24]); and (3) a display mounted on the center of the armrest between the front seat, requiring right rear passengers to look down towards the lower left corner (armrest screen, Tesla Model S/X [15]); (4) a display mounted in the middle of the vehicle roof on the first row (roof screen, Li Auto L9 [25]). Then, we collected the vehicle motion profile in a commuting drive in Guangzhou. Next, we transferred the vehicle motion profile to head motion through a transfer function by Buchheit [2]. Finally, we employed a 6-DoF SVC model [21] to calculate the Motion Sickness Index (MSI) of passengers in different display locations based on head motion calculated from the collected dynamic profile of the vehicle.

Figure 1: The four different display positions investigated in the study.

2.1 Measurement of Head Pose

We used a Volkswagen Magotan to simulate the in-vehicle visual environment. The coordinate system used to describe the head pose is identical to the car-fixed coordinate system, which is established under the right-hand coordinate system according to the convention of ISO 8855 [26], with the z-axis pointing upwards, the x-axis pointing towards the front of the vehicle and y-axis pointing towards the right. The reference position was set when a rear-seat passenger was sitting with an upright back and neutral forward head position. The head poses when the passenger was looking at the displays at different locations were subsequently measured as the rotation angles relative to the reference position. These rotation angles were measured using an IM648 IMU with a sampling frequency of 30 Hz and an accuracy of 0.01 g (1g = 9.8m/s^2) and 0.05°/s for the acceleration and angular acceleration. The IMU was attached to the flat brim of a helmet worn by the participant (see Figure 2). The helmet was tightly secured to the head without slippage between the head and helmet.

Figure 2: The positions of the IMUs for recording the head poses and vehicle dynamic profile.

To enable the analysis of potential individual differences, the measure of the head poses was conducted for 7 participants (6 males, 1 female) between the age of 26 to 31. The participants had a height range of 155-176 cm. It was ensured that all participants had a clear vision and no pre-existing visual impairments that could affect their ability to read the content on the displays. During the measuring procedure, participants were instructed to adopt a standard sitting posture on the rear seat, ensuring their backs were firmly against the seat back and in a relaxed position. The head pose at this position was recorded as the reference head pose. To simulate a real-life scenario of viewing displays, a text was presented on the displays at each position, and participants were required to read the text aloud to confirm that they were actively viewing the display. The duration of measuring process lasted approximately 15 seconds, during which the rotation angles were averaged to obtain (φ_h, θ_h, Ψ_h).

2.2 Collection of Vehicle Dynamic Profile

We used a Volkswagen Magotan to collect the open-road vehicle dynamics profile. Again, the IM648 IMU was used to record the vehicle dynamics. The IMU was affixed to the flat surface of the armrest in the middle of the car to record the vehicle dynamics (see Figure 3). Before recording, the initial acceleration (without gravity) and Euler angle of the IMU were checked to ensure that they were reset to 0 in all axes.

Figure 3: The route for recording vehicle dynamics in University City, Guangzhou, China

To obtain the dynamic vehicle profile in the real-world driving scenario, we did a road data collection starting from 9:00 PM on a Wednesday (see Figure 3). The total distance of the route was 31.2 kilometers and lasted 75 minutes. The route covers urban roads (speed limit less than 60 km/h) and highways (speed limit over 100km/h, 7km out of 31.2km). The traffic was mostly slight, but there was also a small portion of traffic jam with an average speed lower than 15 km/h (around 10 minutes). All roads were well-paved.

2.3 The Motion Transfer Function and 6-DoF SVC

In our study, we adopted a motion transfer function [2] and a 6 DoF SVC model (see Fig. 4) by Buchheit [2] to estimate the MSI, which was found to be effective in estimating the likelihood of experiencing motion sickness during a drive. The 6 DoF SVC model was developed through the integration of neurophysiological insights into the vestibular system, as proposed by Wada et al. [21]. This model enables the acquisition of the MSI at a collective level, utilizing individual head motion data. The vehicle dynamic profile (i.e., g, ⍰ and ⍰) were translated into head motion by considering participants' head pose obtained previously (see Figure 4). The Simulink in MATLAB was used to implement the 6 DoF SVC and motion transfer function in our study.

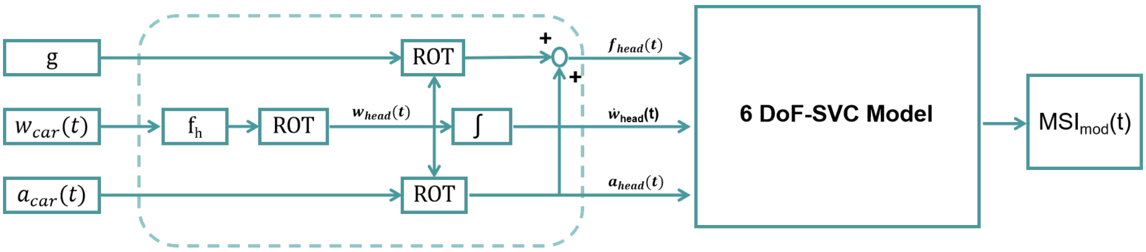

Figure 4: The motion transfer function (Human-Vehicle-Model) and 6-DoF SVC Model adopted from Buchheit et al. [2]; ROT: rotation process; f_h: head-movement factor; g: gravity vector.

3 Results

3.1 Vehicle Dynamics

Previous studies found that low frequencies of lateral acceleration can induce motion sickness in passengers [11]. Specifically, when the frequency of lateral acceleration is at 0.2 Hz, the motion sickness of passengers reached its maximum [5]. In terms of vertical frequency, when non-driving related visual tasks such as watching a video in a vehicle were conducted, the occurrence of retinal slip could lead to motion sickness in the high-frequency range (0.8 Hz to 8 Hz) [3]. In our study, we analyzed the spectral density of the road vehicle dynamics data and found that the dominant frequency of the acceleration remains within the frequency range of interest (0-1 Hz for horizontal acceleration and 0.8-8Hz for vertical acceleration in visual activity) for motion sickness (see Figure 5), which matched the frequency ranges mentioned in previous studies.

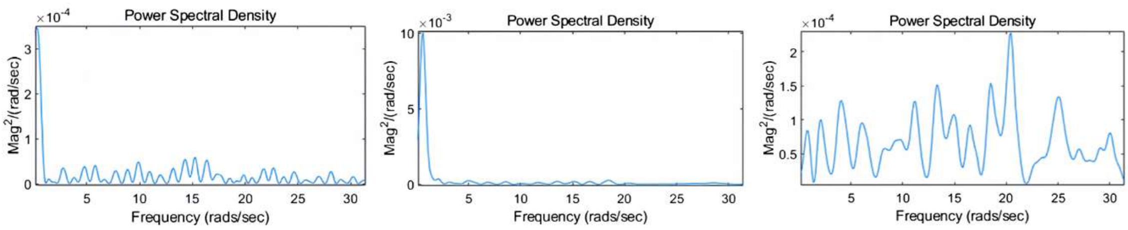

Figure 5: The power spectral density of longitudinal (left), lateral (middle), and vertical (right) acceleration developing with frequency.

3.2 Head Positions

We compared participants' head positions when they looked at the four different display positions to explore the potential individual differences (see Table 1). It was found that the head positions of passengers were highly individual-dependent, even when their sitting position and display locations were identical.

Table 1: The mean (M), standard deviation (SD), and range of the rotation angle for each screen position

	Headrest screen	Backrest screen	Armrest screen	Roof screen
Rotation around x-axis	M: -1.4° SD: 2.2° Range: [-4.1°, .8°]	M: -2.3° SD: 1.7° Range: [-5.4°, -0.3°]	M: -1.9° SD: 2.8° Range: [-5.9°, 2.7°]	M: -0.5° SD: 3.9° Range: [-6.5°,4.4°]
Rotation around y-axis	M: -8.7° SD: 5.9° Range: [-16.5°, -0.4°]	M: -0. 6° SD: 5.2° Range: [-10.0°, 6.0°]	M: 1.7° SD: 5.7° Range: [-9.0°,7.2°]	M: -13.9° SD: 3.8° Range: [-17.1°, -6.8°]
Rotation around z-axis	M: -8.8° SD: 10.2° Range: [-24.8°, 3.9°]	M: -4.7° SD: 6.2° Range: [-12.3°, 2.5°]	M: -28.0° SD: 22.5° Range: [-74.7°, -2.1°]	M: -31.8° SD: 18.5° Range: [-56.3°, -9.1°]

3.3 MSI based on 6-DOF SVC

Given a within-subject design was used (each participant looked at four display locations), a Friedman test was conducted to analyze the difference in final MSI (the calculated MSI at the end of the 75 min drive) among the four display positions with the display location as the only independent variable (see Figure 6). The results showed that there was a significant difference in MSI among the four display positions (p = .03). Thus, a post hoc analysis with the Nemenyi test for pairwise comparisons between each display location was conducted. The Bonferroni correction was adopted. We found only a marginally significantly result was found between armrest display and roof display (p =.08), with roof display leading to higher MSI compared to that of armrest display; all other pairwise comparisons were non-significant (p > .1).

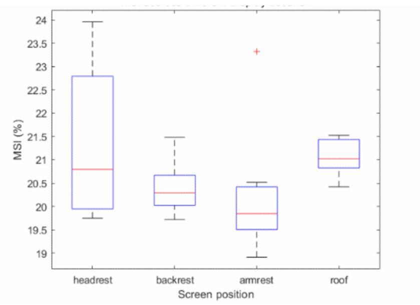

Figure 6: The boxplot of the simulated MSI at the end of the drive-in different display position

4 DISCUSSION

Motion sickness in vehicles is influenced by various factors, including vehicle dynamics, head motion [18], anticipation of vehicle motion [18], and perception of the road environment [1]. Previous research has primarily focused on the effects of providing artificial motion cues in alleviating motion sickness. However, the location of the display is also expected to have an impact on motion sickness due to its influence on both the perception of the road environment and head motion.

Using a simulation based on the motion transfer function and the dynamic vehicle profile we collected in an on-road test, we compared the MSI induced by in-vehicle screens at four different locations. First, we observed obvious individual differences in drivers' head positions even when participants were looking at the display at the same location. The participants' height and individual pose preference for looking at the displays may account for the difference in their head positions. In-experiment observations show that some participants prefer to fully align their heads with the direction of the display, while others only partially align their heads and compensate for inadequate head rotation with eye movements.

Furthermore, a marginally significant difference was observed in the MSI between the armrest display and the roof display integrated within the vehicle. Notably, the armrest display led to the lowest MSI value, as depicted in Figure 6. Previous research has found that the displays at higher locations (e.g., near the windshield) were less likely to lead to motion sickness compared to displays at lower locations [10]. Thus, there seem to be conflicts between the objectives of minimizing motion-related motion sickness versus maximizing the perception of ego motion. Nevertheless, it should be noted that our results were derived from simulations conducted using established theories that solely account for head motion. As a next step, to quantify the contribution of visual motion cues versus head motion, we will need to collect more data from more participants and conduct an on-road experiment to compare passenger's motion sickness levels, when motion cues were present versus absent.

Overall, by combining theoretical simulations with partial on-road data collection, we conducted a comprehensive investigation into the impact of display location on drivers' motion sickness levels during a typical city trip. Though with a limited sample size, the results have shown some level of differences between display locations, in terms of motion sickness induction from a head motion perspective of view. This work validated the feasibility of our research framework and provide valuable insights into the plan for future road-test.

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