Adaptive In-Vehicle Virtual Reality for Reducing Motion Sickness: Manipulating Passenger Posture During Driving Events

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Abstract

The rise of autonomous vehicles (AVs) has promoted the adoption of in-vehicle virtual reality (VR) for creating immersive experiences. However, these experiences can trigger motion sickness (MS) due to visual-vestibular mismatches. Traditional techniques, such as visual matching and scene manipulation, address MS but often neglect the impact of body posture changes. This study examines the effects of interactive VR tasks on passenger body posture during MS-inducing events, including turns and vertical displacements. Our findings reveal significant variations in user body postures relative to conditions with event-based designed interactive VR tasks, resulting in a reduction of MS symptoms. Specifically, participants engaged in interactive VR tasks showed improved posture alignment and body stability. These insights offer practical guidelines for developing adaptive VR content that proactively manages posture to alleviate MS, thereby enhancing passenger comfort in in-vehicle VR applications.

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CCS Concepts

• **Human-centered computing → Virtual reality**; **Haptic devices**.

Keywords

sensory alignment; In-vehicle virtual reality; motion sickness; visual cues; kinesthetic feedback; haptic feedback

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1 Introduction

Advancements in autonomous vehicles (AVs) allow passengers to engage more in non-driving activities [1, 2], such as using smartphones, working on laptops, reading, or having a more immersive experience through virtual reality (VR) headsets [12]. These activities can often lead to motion sickness (MS) due to a visual-vestibular mismatch [7]. Various in-vehicle movements can trigger this mismatch, especially when the passenger's vision is entirely occupied by the head-mounted display (HMD) [4, 6, 22, 23]. Passenger body posture within a vehicle, especially during turning events, vertical displacements, and inconsistent vehicle movements, significantly contributes to MS due to misalignment between the body and environmental changes [8, 9, 14]. For example, drivers experience less MS because they adapt their posture in anticipation of events, such

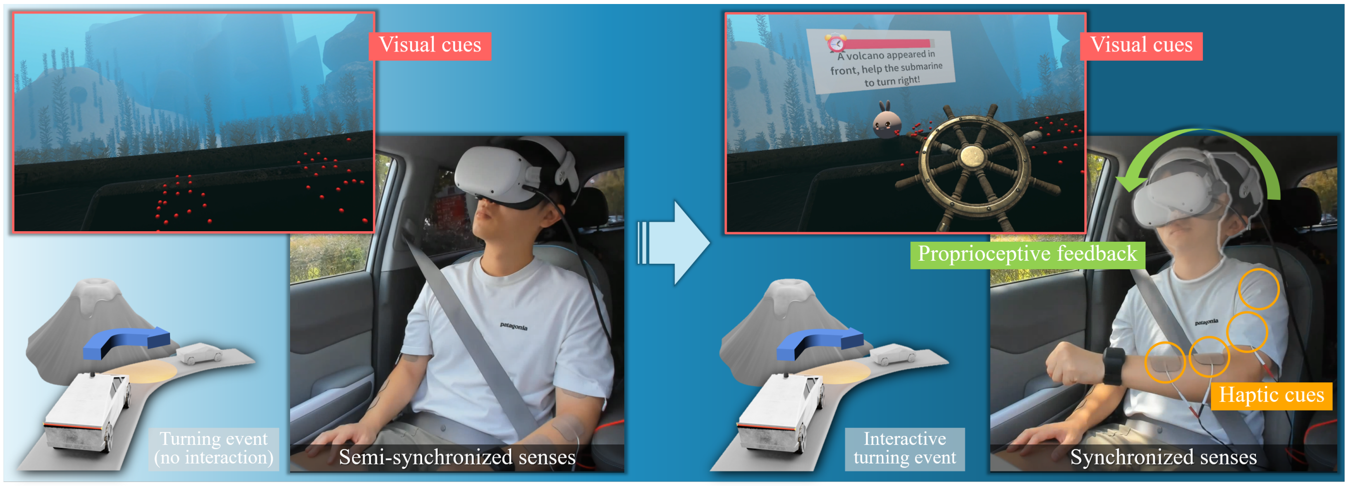


Figure 1: Impact on passenger posture under different virtual reality conditions during the same movement of a real vehicle.

as tilting their heads toward the center of a turning curve. Similarly, passengers who mimic this adaptive posture by tilting their heads toward the turn curve's center report a substantial decrease in MS [20, 21].

Pöhlmann et al.'s study [17] employed audiovisual cues in a simulated motion environment using a rotating chair to enhance passenger comfort. This was achieved by enforcing postural stability through the ergonomic positioning of the virtual display. Holoride and similar research [10, 11] have focused on synchronizing VR scenes with vehicle movements, primarily relying on visual and auditory cues to reduce MS.

Expanding on these approaches, the SYNC-VR framework [5] further synchronized the vehicle's motion with the virtual environment (VE). It integrated visual cues with interactive inputs and haptic feedback via electrical muscle stimulation (EMS) to elevate passengers' sense of presence and combat MS. This design aids passengers in anticipating and responding to upcoming vehicle movements [16], particularly during MS-inducing events such as turns and bumps, thereby enhancing their resilience against MS. While this method has shown promising results in mitigating MS, the impact of body posture changes induced by interactive VR tasks on MS remains underexplored. Our current investigation leverages SYNC-VR as a basis to explore how interactive VR tasks can influence passenger body posture during MS-inducing events. Our study aims to investigate the effects of proprioceptive feedback, generated by passengers moving their bodies during interactive VR tasks, within a moving vehicle Fig.1. Therefore, this work is guided by the following questions:

- How do interactive tasks in the SYNC-VR setting influence passenger posture?
- Can posture manipulation through these tasks reduce the feeling of MS?
- What are the best practices for designing and delivering interactive tasks to enhance overall passenger comfort in VR environments within moving vehicles?

By addressing these questions, our study aims to develop adaptive VR content that enhances comfort and experience in in-vehicle VR applications.

2 Procedure

As a complementary study to [5] that investigated the relationship between MS and the synchronization of multiple sensory inputs, this research further explores this field by examining the role of VR interactive content in manipulating and regulating the passenger's body posture during driving events, which are known triggers for MS discomfort [3, 18].

2.1 Methodology

The setup and experimental procedure follow those outlined in [5]. Each participant was exposed to four distinct experimental conditions, characterized by the same driving events (e.g., two turning events, three vertical displacement events, and two inconsistent motion events) Fig. 2. Within each condition, participants experienced varying degrees of sensory synchronization.

(1) Condition 1, "Baseline–no visual cues," a disparity exists between the physical movement of the vehicle and the visual input perceived through the HMD.
(2) Condition 2, "Visual cues only," involves congruent visual input aligned with the actual vehicle motion, enhanced by engaging auditory stimuli.
(3) Condition 3, "Visual cues and interactions," features congruent visual input aligned with the actual vehicle motion, enriched by interactive virtual tasks and engaging auditory stimuli.
(4) Condition 4, "visual cues, interactions, and EMS feedback," incorporates congruent visual input synchronized with actual vehicle motion, augmented by interactive virtual tasks, haptic feedback, and engaging auditory stimuli.

In Conditions 3 and 4, all participants were required to perform interactive tasks designed to respond to each driving event. For instance, during the turn events, participants assisted a virtual submarine in turning right or left to avoid collisions by rotating a virtual steering wheel. During the vertical displacement events (crossing over a speed bump), participants observed virtual water turbulences corresponding to the real speed bump locations and were asked to hold a virtual bar while crossing. For the inconsistent motion events (sudden stops and starts), participants encountered a virtual wall blocking the navigation path and were tasked with using a virtual hammer to destroy it, allowing the virtual submarine to continue its route. For all events, the positions in the VE were calibrated to match the corresponding events in the real-world environment Fig. 2. The real vehicle movement was tracked using a GPS-RTK Dead Reckoning Breakout-ZED-F9R [19] (Qwiic) module.

The major difference in Condition 4, compared to Condition 3, is that participants received haptic feedback using EMS-customized devices. These devices simulated the force applied to the participants' arms when interacting with the virtual objects.

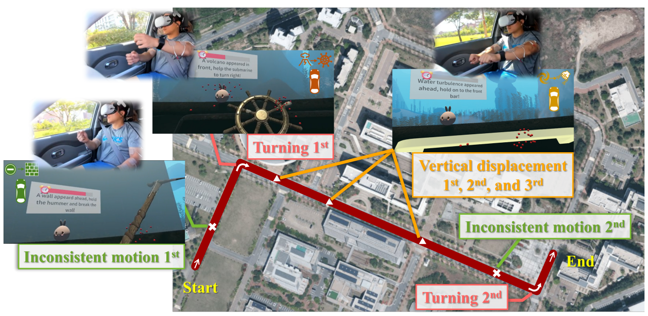


Figure 2: Experimental route and interactive tasks.

2.2 Tracking Participant Posture

To understand the influence of each driving event under different experimental conditions on participant posture, we tracked body landmarks from recorded videos of the participants. For this analysis, we randomly selected a subset of four participants from the main sample group described in [5].

To obtain the posture information, we employed the MediaPipe holistic model [15]. This model enables simultaneous tracking of human pose, face landmarks, and hand movements at CPU speeds.

In this study, we focused on evaluating posture differences during two specific driving events: the first turn event and the first vertical displacement event Fig. 2. By analyzing these events, we aimed to identify variations in posture that could contribute to our understanding of motion sickness mitigation in the context of VR usage in moving vehicles.

2.2.1 Overall Body Tilt Calculation. To evaluate changes in the participant's body posture during the vehicle turn event, we calculate the body tilt angle. This is achieved by determining a tilt vector, which ideally aligns at 90 degrees when the participant is in a neutral posture, not tilting to the right or left. The tilt vector's angle increases as the participant tilts to the right and decreases when the participant tilts to the left. The tilt angle is derived from two components: the tilt calculated from shoulder landmarks (right and left shoulders) and the tilt calculated from facial landmarks (nose, ears, and eyes).

First, we identify the positions of the left and right shoulder landmarks and calculate the angle formed between these two points. This initial measurement provides the primary indication of body tilt. To refine the tilt calculation, we also utilize facial landmarks, specifically the positions of the nose, left and right ears, and inner corners of the eyes. By extracting the coordinates of these facial landmarks, we can compute the angles formed by these points to account for head yaw. This secondary measure ensures that head movements, which can influence perceived body tilt, are also considered.

This process involves adjusting the tilt angle based on the initial neutral posture, providing a centered measurement that accounts for any initial posture differences. During driving events, we then calculate the relative tilt angle by referring it to this initial tilt value Fig. 3(a), and Fig. 3(b).

2.2.2 Calculating Body Vibration. To calculate the vibration component of the participant's body and determine the intensity of shaking during vertical displacement events, particularly when crossing over a speed bump, we analyze the displacement of specific landmarks over consecutive frames.

We begin by tracking the positions of key facial landmarks, including the nose, left and right ears, and inner corners of the eyes, as well as the left and right shoulder landmarks. For the initial frame, we store the coordinates of these landmarks to establish a reference point. In each subsequent frame, we retrieve the current coordinates of the identified landmarks. We calculate the vibration intensity by measuring the displacement of these landmarks from one frame to the next. Specifically, we compute the Euclidean distance between the positions of each landmark in consecutive frames. We obtain the total displacement for each frame by averaging the individual displacements of these landmarks Fig. 3(c), and Fig. 3(d).

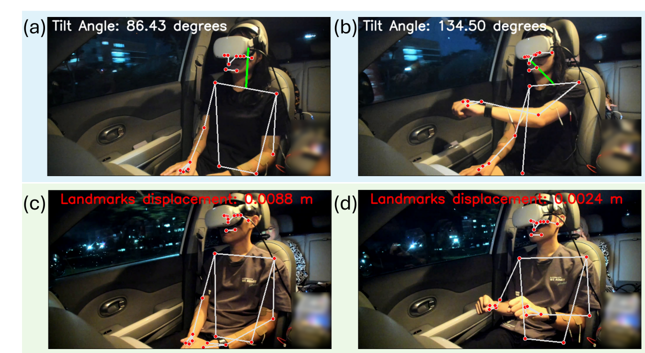
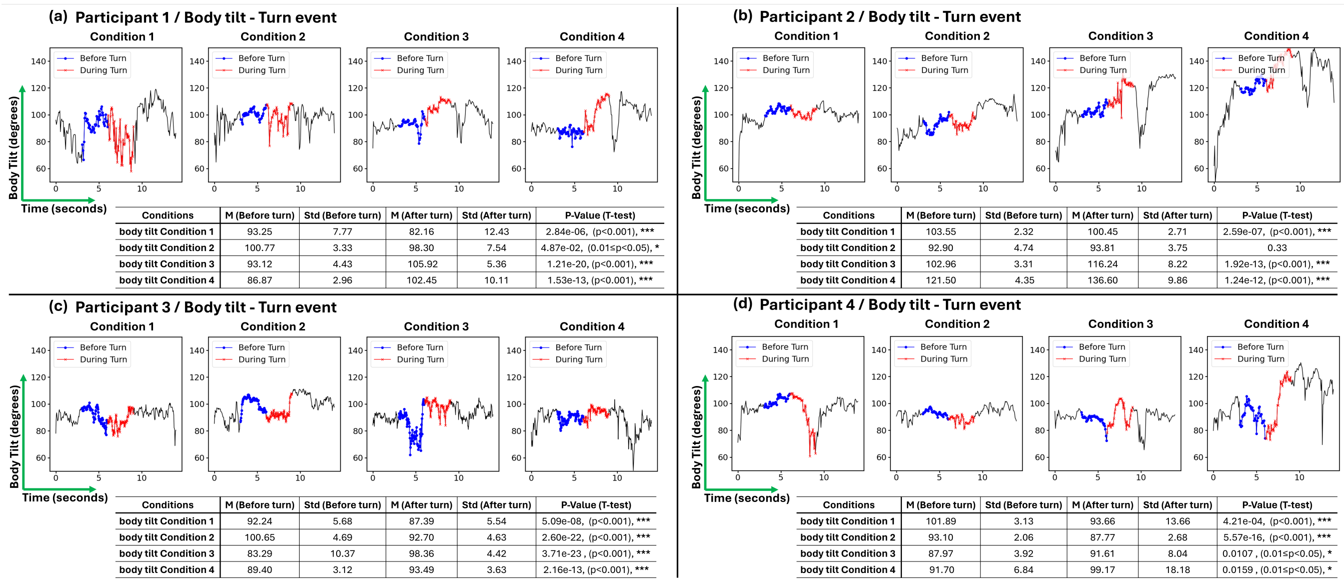


Figure 3: (a) and (b) Body tilt during a turn event without/with an interaction task, respectively. (c) and (d) Body landmark displacement during a vertical displacement event without/with an interaction task, respectively.

3 Results and Discussion

Body Tilt in Turn Event: Drivers experience less MS than passengers primarily because they adapt their body posture in anticipation of upcoming events. For instance, drivers tilt their bodies toward the center of a curve when navigating a turn, whereas passengers



(a)

Conditions	M (Before turn)	Std (Before turn)	M (After turn)	Std (After turn)	P-Value (T-test)
body tilt Condition 1	93.25	7.77	82.16	12.43	2.84e-06, (p<0.001), ***
body tilt Condition 2	100.77	3.33	98.30	7.54	4.87e-02, (0.01≤p<0.05), *
body tilt Condition 3	93.12	4.43	105.92	5.36	1.21e-20, (p<0.001), ***
body tilt Condition 4	86.87	2.96	102.45	10.11	1.53e-13, (p<0.001), ***

(b)

Conditions	M (Before turn)	Std (Before turn)	M (After turn)	Std (After turn)	P-Value (T-test)
body tilt Condition 1	103.55	2.32	100.45	2.71	2.59e-07, (p<0.001), ***
body tilt Condition 2	92.90	4.74	93.81	3.75	0.33
body tilt Condition 3	102.96	3.31	116.24	8.22	1.92e-13, (p<0.001), ***
body tilt Condition 4	121.50	4.35	136.60	9.86	1.24e-12, (p<0.001), ***

(c)

Conditions	M (Before turn)	Std (Before turn)	M (After turn)	Std (After turn)	P-Value (T-test)
body tilt Condition 1	92.24	5.68	87.39	5.54	5.09e-08, (p<0.001), ***
body tilt Condition 2	100.65	4.69	92.70	4.63	2.60e-22, (p<0.001), ***
body tilt Condition 3	83.29	10.37	98.36	4.42	3.71e-23 , (p<0.001), ***
body tilt Condition 4	89.40	3.12	93.49	3.63	2.16e-13, (p<0.001), ***

(d)

Conditions	M (Before turn)	Std (Before turn)	M (After turn)	Std (After turn)	P-Value (T-test)
body tilt Condition 1	101.89	3.13	93.66	13.66	4.21e-04, (p<0.001), ***
body tilt Condition 2	93.10	2.06	87.77	2.68	5.57e-16, (p<0.001), ***
body tilt Condition 3	87.97	3.92	91.61	8.04	0.0107 , (0.01≤p<0.05), *
body tilt Condition 4	91.70	6.84	99.17	18.18	0.0159 , (0.01≤p<0.05), *

Figure 4: Tracking the body tilt of four participants across four experimental conditions during the turning event.

often move their bodies in the opposite direction [20]. Based on this observation, we propose that an interactive task that encourages passengers to tilt their bodies towards the center of the turning curve while immersed in a VE can help mitigate MS during vehicle turning events.

To understand the body tilting patterns in response to vehicle turning events, we analyzed and compared body tilt angles 3 seconds before and 3 seconds after the turn across four conditions. The paired t-test showed a significant decrease in body tilting in both Condition 1 and 2, where participants predominantly tilted their bodies in the opposite direction of the turn curve center, indicating a reactive posture adjustment. Conversely, a significant increase in body tilting was observed in both Condition 3 and 4, where participants primarily tilted their bodies in the same direction as the turn curve center, demonstrating a proactive posture adjustment Fig. 4.

When participants were involved in an interactive task (rotating a steering wheel to assist a virtual submarine turning right), they successfully tilted their bodies to the right in Conditions 3 and 4. Conversely, in Conditions 1 and 2, where participants watched a static VE (Condition 1) or a visually synchronized VE without interaction (Condition 2), their bodies tilted significantly in the opposite direction. This supports previous findings [5] that Conditions 1 and 2 led to significant feelings of MS, while Conditions 3 and 4 did not.

An interesting observation was made with participant 2, who tilted their torso left but their head right during the vehicle's right turn in Condition 2. This defensive posture disrupted the usual pattern observed in Condition 2 Fig. 4(b). As the tilt vector is constructed by tracking the torso component (represented by shoulder landmarks) and the head component (represented by selected facial landmarks), it is important to track the passenger's head and body independently. This helps us be aware of complex or unexpected postures that passengers may adopt as a defensive mechanism or during long trips. Understanding the detailed postural information has the potential to help design custom VR interactive tasks that assist passengers in correcting their posture in advance as a response to an upcoming driving event, thereby protecting them from MS.

Body Vibration in Vertical Displacement Event: We analyzed landmark displacement data as a representation of participant body vibration, focusing on 2 seconds before and 2 seconds after the vehicle started crossing over the speed bump. This analysis was conducted across four conditions using repeated measures ANOVA with Bonferroni's post hoc test. The overall analysis revealed significant differences for all participants, highlighting how various experimental conditions impact passengers' body stability. For participant 1, $F(3, 135) = 9.06$, $p < .01$; for participant 2, $F(3, 126) = 4.68$, $p < .01$; for participant 3, $F(3, 261) = 5.49$, $p < .01$; and for participant 4, $F(3, 126) = 6.73$, $p < .01$.

Pairwise comparisons indicated a significant increase in body vibration in Condition 1 compared to Conditions 3 and 4. However, no significant differences were observed for most participants between Conditions 1 and 2, or between Conditions 3 and 4.

These findings emphasize the importance of involving participants in interactive tasks that help stabilize their bodies. The proposed interactive tasks improved body stability in Conditions 3 and 4 compared to Conditions 1 and 2. Condition 1, where participants experienced a static scene, led to the highest mean value of body vibration. In Condition 2, participants observed synchronized visual input aligned with the vehicle's route, including visual cues such as water turbulence at the actual speed bump location. Consequently, Condition 2 showed lower mean vibration values compared to Condition 1, as participants anticipated the upcoming event through visual cues, preparing their bodies for the disturbance.

Conditions 3 and 4 exhibited the lowest mean values for body vibration, likely because holding a virtual object gave participants a realistic feeling of attachment, similar to holding the vehicle's grab handles in real life to support body stability. This aligns with findings in [5], where participants perceived no motion sickness in Conditions 3 and 4 but experienced significant motion sickness in Conditions 1 and 2. One reason for this is the reduction in vibration intensity in Conditions 3 and 4, which, along with other factors, contributed to the absence of MS in these conditions.

Understanding individual differences in sensitivity to vehicle dynamics is crucial for developing personalized VR content that enhances passenger comfort. For instance, VR systems could incorporate real-time adjustments based on detected body posture and vibrations to provide adaptive interactive content, minimizing motion sickness.

4 Conclusion and Future Work

Our study highlights the importance of incorporating vehicle dynamics, passenger body posture, and anticipation of real-world disturbances in the design of VR content to minimize motion sickness (MS) during various driving events. While vision techniques and machine learning solutions can determine passenger posture, as demonstrated in this study, they raise privacy concerns. Future work will focus on developing embedded in-seat sensors powered by AI posture detection models [13] to assess passenger posture in real-time, alongside head tracking data from the HMD. This approach will significantly aid in designing adaptive VR content, providing a concrete and effective solution to enhance passenger comfort and reduce motion sickness.

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