I Want to Break Free: Enabling User-Applied Active Locomotion in In-Car VR through Contextual Cues

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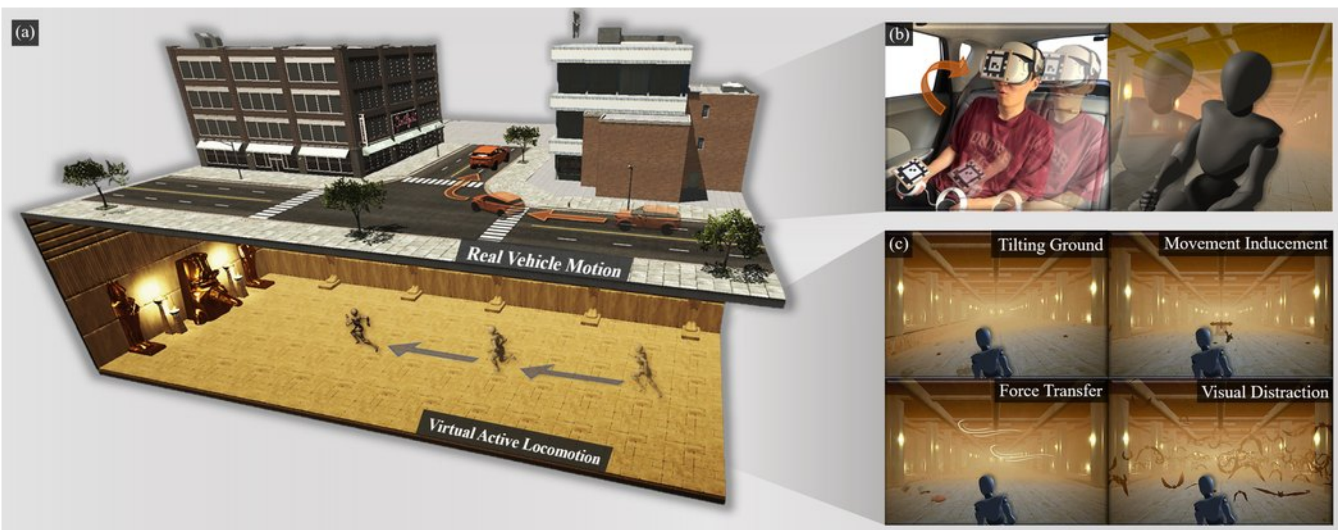

Figure 1: (a) Visualization of user-applied active locomotion in-car, with the user moving forward in VR while the real vehicle turns right. (b) Depiction of the user shifting left due to centrifugal forces from the vehicle's right turn and its concurrent mapping in the virtual environment. (c) Illustrations of translating vehicle motion while allowing freedom of movement through the implementation of contextual cues.

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Abstract

We explore the feasibility of active user-applied locomotion in virtual reality (VR) within in-car environments, diverging from previous in-car VR research that synchronized virtual motion with the car's movement. Through a two-step study, we examined the effects of locomotion methods on user experience in dynamic vehicle environments and evaluated contextual cues designed to mitigate

sensory mismatch caused by vehicle motion. The first study evaluated five locomotion methods, identifying joystick-based navigation as the most suitable for in-car use due to its low physical demand and stability. The second study focused on designing and testing contextual cues that translate physical sensations of vehicle motion into virtual effects without limiting the user's freedom of movement, with results demonstrating their effectiveness in reducing motion sickness and enhancing presence. We conclude with initial insights and design considerations for expanding upon our findings in regards to enabling active locomotion in in-car VR.

CCS Concepts

• **Human-centered computing → Virtual reality**.

Keywords

In-Car, Virtual Reality, Locomotion, Visual Cues, User Experience, Motion Sickness, Sensory Mismatch

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1 Introduction

The adoption of immersive virtual reality (VR) applications is rapidly expanding across diverse environments and platforms. This growth is not limited to traditional settings like users' homes but extends to dynamic environments such as in transit, including cars [2, 43, 53, 71, 103], trains [63], ships [76], and airplanes [72, 73, 109], where VR usage is becoming increasingly feasible.

In particular, the integration of VR for passengers, referred to as in-car VR [15, 49, 69], has garnered recent growth in research attention. Early works in this area by Hock et al. [43] and McGill et al. [69] introduced the concept of synchronizing the movement of the real vehicle with the virtual movement experienced by the VR user. This synchronization aligns the visual perception of virtual movement with the kinesthetic and vestibular feedback from the actual vehicle's motion, enhancing presence and reducing motion sickness [43]. This concept has since become a baseline factor in subsequent in-car VR, where the virtual content typically simulates the experience of being a passenger in a virtual vehicle—such as an automobile [71], helicopter [43], or submarine [22, 49].

However, this approach imposes inherent limitations on the user's freedom of movement within the virtual environment. Since virtual movement is coupled with the real vehicle's dynamics, the position and orientation of the user are dependent on external driving events such as accelerations, turns, and stops. In other words, the user is rendered passive in terms of their own position, unable to navigate independently within the virtual environment. This aspect of passivity was reflected in past feedback as well, where McGill et al. [69] noted that several participants of their user study expressed dissatisfaction regarding the lack of control when their virtual movement was synchronized with the real vehicle.

Our study aims to address these limitations by introducing active locomotion to in-car VR, enabling users to navigate the virtual environment independently of vehicle motion. Research indicates that user-controlled navigation within VR environments can enhance spatial presence and interaction quality, both major factors for immersive experiences [58, 92, 96]. Active locomotion also provides users with greater flexibility to explore virtual environments, allowing for use cases requiring detailed spatial interactions such as training or exploration. As such, enabling active locomotion in-car has the potential to open up a broader range of applications while extending its utility in terms of entertainment and productivity.

However, decoupling the user's virtual movement from the car's physical movement introduces challenges related to presence and motion sickness—issues that the original method of synchronization were specifically designed to address. Without synchronization, the risk of sensory mismatch between visual and vestibular cues increases, which can lead to increased motion sickness [3, 70, 81, 90] and reduced presence [98, 108]. To address these challenges, we aim to: (1) identify which VR locomotion method is most compatible with in-vehicle use, and (2) propose the implementation of *contextual cues* within the virtual environment, with the purpose of contextualizing the physical sensations of vehicle movement while maintaining freedom of locomotion for the user.

To evaluate the feasibility of active locomotion in an in-car VR setting, as well as assess the effectiveness of the proposed contextual cues, we conducted two consecutive user studies via an implemented VR setup within a moving vehicle. In the first experiment (E1), we investigated different locomotion methods possible for an in-car passenger, focusing on their impact on motion sickness, presence, perceived load, and user preference in both a stationary indoors and dynamic vehicle setting. Qualitative feedback was also gathered to further understand users' perception on the experience of each method, including how specific driving events such as sudden decelerations and sharp turns [22, 49] influenced the active locomotion experience in the in-car VR context.

Based on the findings from E1, we identified the method best suited for active locomotion in in-car VR and determined driving events for which to apply contextual cues. Subsequently, a focus group interview (FGI) and following convergence session finalized the design of four contextual cues to be tested in the subsequent experiment (E2). By comparing with a locomotion baseline, E2 evaluated the effectiveness of these cues in enhancing the active locomotion experience, focusing on measures of motion sickness, presence, perceived load, and user preference. Through the results and analyses of both studies, we provide a multitude of design considerations for future implementations of locomotion methods and contextual cues, contributing to the feasibility, comfort, and enhanced enjoyment of active locomotion in in-car VR.

The main contributions of our study are as follows:

(1) Provides the first systematic examination of the impact of virtual active locomotion on motion sickness, presence, and perceived load within an in-vehicle setup, compared to a stationary room setup.
(2) Evaluates the usability and user preferences for various virtual locomotion methods in the context of active locomotion in in-car VR, independent of the vehicle's movements.

(3) Illustrates the design and strategic implementation of different contextual cues aimed to reduce motion sickness and enhance presence, while maintaining freedom of movement during active locomotion in in-car VR.
(4) Demonstrates the feasibility of active locomotion in in-car VR while maintaining usability through the application of contextual cues, offering guidelines for future design considerations to further enhance the in-car VR active locomotion experience.

2 Related Works

2.1 In-Car VR and its Integration of Vehicle Motion

Advancements in VR technology have opened up new possibilities for virtual content use, particularly for using VR headsets as systems for passengers in automobiles [69]. Since then, in-car VR applications both commercially and in research have expanded to range from productivity tasks [59, 60, 62, 84, 87] and realistic on-road simulations [8, 31, 32, 112], to immersive content for tourism [71], soothing comfort [79], and entertainment [2, 22, 43, 49]. McGill et al. were among the first to address the challenges of mitigating sensory mismatch and consequent motion sickness in in-car VR, linking it to the discrepancy between visual motion perception and the physical sensations of vehicle movement [69]. Since then, various strategies have been developed to reduce motion sickness in in-car VR, such as directly aligning the virtual content with the car's movements through visual synchronization [15, 22, 43, 69, 71, 82], embedding subtle cues in the VR content addressing vehicle motion [36, 86, 87], or displaying situational awareness cues for direct information access [24, 61]. Most of these applications do not involve user-applied active locomotion, but instead feature content where the user moves passively along the route of the real vehicle.

However, recent studies have begun exploring the potential of in-car VR beyond the previous concept of 1:1 mapping between real and virtual motion. Pohlmann et al. [84] evaluated in-car VR scenarios where translational gains and attenuations were applied to virtual movement, finding that faster speeds increased excitement and slower speeds enhanced productivity. Similarly, Lu et al. [63] investigated VR motion that deliberately diverges from a vehicle's physical movements during transportation, discovering that such divergence enhances immersion, entertainment, and overall user experience, while also highlighting user-applied active locomotion as a promising area for future research. Gim et al. [30] partially explored the potential of user-applied active locomotion in in-car VR using steering gains, allowing users to control their virtual direction independently of the vehicle's velocity. Our research builds upon these previous works in that we aim to examine the feasibility of active locomotion independent from the motion of the vehicle, including velocity and direction.

2.2 Active Locomotion in VR

Locomotion is a vital aspect of VR interactions, allowing users to navigate and explore virtual environments effectively [4, 35]. The primary advantage of user-applied locomotion lies in its ability to expand the interactive virtual environment, thereby enhancing the variety and complexity of VR experiences compared to stationary contents [6, 58]. In addition, locomotion can increase user engagement, presence, and spatial cognition [16, 92, 96], and also decrease motion sickness as users are better able to predict and synchronize their actions with the visual feedback in the virtual environment [12, 21]. While the term of locomotion is typically associated with active locomotion in which the user has control over their own navigation, passive locomotion in which the user is riding an automated virtual vehicle [22, 43] or following a predetermined path [91] has also been incorporated in VR contents. However, passive locomotion has been shown to negatively affect user experience in some studies, primarily due to the user's lack of control and subsequent inability to predict their own movement within the virtual environment [21, 64, 69]. We aim to introduce user-applied active locomotion specifically to in-car VR, differentiating from previous applications which predominantly featured passive locomotion and expanding the scope of applicable virtual contents.

The choice of locomotion technique is critical for enhancing user experience in VR, significantly impacting factors such as cybersickness or presence, as evidenced by multiple method development and comparison studies [4, 9, 17, 27, 104]. While walking is generally considered the most natural and embodied locomotion method [27, 104] due to its biomechanical symmetry with natural movement [1], the problem of effective locomotion in constrained environments remains an ongoing challenge, which previous works have attempted by utilizing additional hardware (e.g. treadmills [20, 74]) or implementing techniques that do not involve real-world walking [7, 9, 19, 40]. Potential methods for such environments, including that of the constrained space of a passenger seat within a vehicle [68, 70, 110], include joystick or controller-based movement [9, 57], upper-body or head leaning [40, 66, 95], teleportation [7, 28, 67], grab-and-pull [19, 26], and walking-in-place while seated [11]. Although numerous studies have compared the usability of these methods in stationary indoors settings [9, 11, 57, 104], the impact of usability of these methods in moving vehicles has not been thoroughly evaluated. Thus, as a distinct contribution of our study, we compared various potential locomotion methods in both stationary and in-vehicle VR setups. This comparison examines how user experience factors, such as motion sickness, presence, and overall preference, are influenced by the motion of a vehicle, aiming to identify the VR locomotion method best suited for in-vehicle use while minimizing negative impacts on user experience.

2.3 Translating Real-World Sensory Inputs into VR

Due to the immersive nature of VR, physical sensations from the real environment, such as external sounds and touch [97], can disrupt a user's engagement and diminish their sense of presence within the virtual environment [29, 107]. To combat this, relevant research has developed methods to maintain or even enhance presence by seamlessly incorporating real-world sensations into VR content [13, 23, 37, 39, 102]. Tao & Lopes [102] provided a comprehensive overview of such methods by implementing and evaluating various cues designed to contextualize real-world sensations, such as visualizing auditory sources within a virtual environment to match real-world sounds like laughter or footsteps.

Figure 2: (a) 6-DoF tracking setup in the passenger seat of a vehicle, with an integrated tracking platform. (b) Visualization of fiducial marker detection between the two ZED2i cameras, translated into position tracking within VR. (c) Explanation of the compensation method utilized by the IMU sensor fixed to the vehicle for headset rotation tracking.

In dynamic in-car environments, a variety of distractions can affect the user's VR experience, usually related to a lack of awareness regarding vehicle motion [24, 52]. These distractions include the vestibular sensations of the vehicle's motion [43, 69, 70, 81] and the kinesthetic and haptic sensations from posture shifts induced by inertial forces during vehicle acceleration [22, 30, 43, 44], both of which were found to harm in-car virtual interactions [18, 71, 75]. The primary method used to integrate these distractions is the concept of synchronizing virtual movement with the vehicle, thereby contextualizing the physical stimuli regarding vehicle movement [22, 43, 49, 69, 71, 79]. Additionally, some studies have attempted to further minimize sensory mismatch by incorporating multimodal interactions, such as using audiovisual cues [83] or haptic feedback [22], although these methods were implemented in alignment with the aforementioned motion synchronization approach.

These methods correspond to Tao & Lopes' definition of direct mapping [102], in which the motion of the real vehicle is translated directly into virtual movement. However, for user-applied active locomotion to be feasible in a vehicle, such direct mapping is not possible without limiting the user's freedom of navigation. Therefore, to minimize sensory mismatch while enabling active locomotion, we deemed it necessary to implement cues that align with stretch mapping [102], wherein physical sensations related to vehicle movement are translated into other elements that fit within the context of the virtual environment. As an example, Qiu et al. [88] implemented *Physics-Based Cues*, in which vehicle motion was not directly conveyed but implicitly represented in the movement of swinging objects within the virtual environment.

We draw from these multitude of research fields to address the problem of passive locomotion in-vehicle, and present potential solutions to sensory mismatch during active locomotion in the form of contextual cues, inspired by the integrating of real-world distractions in traditional VR. In doing so, our study builds upon the current literature to evaluate the feasibility and potential of active locomotion in in-car VR.

3 In-Car VR Apparatus

The dynamic environment of a moving vehicle presents multiple technical challenges in headset and controller tracking for typical standalone 6-DoF (Degree of Freedom) headsets, such as the inability to differentiate between absolute pose and relative pose in reference to the vehicle [71]. Thus, previous studies in in-car VR have utilized integrated platforms using multiple sensors regarding vehicle movement, such as the use of external Inertial Measurement Units (IMUs) or Global Navigation Satellite System modules, to maintain 3-DoF or 6-DoF headset tracking within the vehicle [22, 32, 43, 69, 71, 113]. For our procedure of evaluating multiple locomotion methods in E1 as well as the implementation of contextual cues in E2, both of which require pose data such as head and controller position, we implemented a 6-DoF tracking in-vehicle setup capable of positional/rotational tracking of the headset and positional tracking of the controllers, through a fusion of sensing methods including rotational tracking via IMU and outside-in optical tracking by pose estimation using fiducial markers.

3.1 Hardware Components

The following hardware components were used in the setup, where the user was situated in the passenger seat of a KIA Soul EV, as shown in Figure 2-(a).

- **Processing Unit**: An ASUS MSI GE66 Raider 11UH laptop was used as the main processing unit for tracking and VR rendering capabilities.
- **VR Headset and Controllers**: For virtual integration, we used the head-mounted display (HMD) and controllers of a Meta Quest 2.
- **Fiducial Markers (HMD, Controller, Right Leg, Left Leg)**: Four AprilTag markers (tagStandard41h12, IDs 0-3) were used as the fiducial markers to estimate and translate position data. These markers were chosen due to their relatively low cost and latency, as compared to heavier solutions

such as detecting point-cloud data [22, 71] or infrared tracking systems [34].

- **Stereo Cameras (Forefront, Ceiling)**: For the tracking of the fiducial markers, two ZED2i stereo cameras were fixed at the forefront of and above the passenger respectively, chosen due to their flexibility in balancing resolution and frame rate and wide horizontal FOV for robustness of marker detection.
- **IMU**: The EBIMU24GV52 IMU sensor module, consisting of a wireless sensor and connected receiver, was fixed at the center point of the vehicle and used as a base reference point representing the vehicle's rotation.
- **Additional Components**: While not absolutely mandatory for the operation of the system, we also used a ring light attached to the front seat for consistent lighting for night-time experiments, and a blackout shade to the car window directly beside the passenger to further improve tracking performance and accuracy in varied weather conditions.

3.2 6-DoF Tracking Capabilities

Positional tracking of the HMD, controllers, and legs are achieved through the ZED2i stereo cameras and fiducial markers. The forefront ZED2i camera tracks the marker attached to the HMD, while the ceiling-mounted ZED camera tracks the markers attached to the controller and legs, as shown in Figure 2-(b). The system calculates the HMD's position via perspective-n-point algorithm [25], in which the 2D coordinates of the detected marker corners in the camera image are matched with their known 3D positions in the marker's local coordinate system for accurate pose estimation. The positional data of each marker is detected and scaled to align with the virtual environment, while the built-in HMD positional tracking is disabled to rely exclusively on the marker data, ensuring the user's position within the VR environment is consistent and independent of the vehicle's motion.

For tracking of the user's head rotations within the vehicle, we implemented a calibration method used in previous in-car VR research [22, 43, 69, 71, 112] that separates the rotational data of the HMD from the vehicle's movements via a fixed IMU monitoring the vehicle's orientation in a global reference frame. This, coupled with the positional tracking from the aforementioned visual odometry, allows for 6-DoF tracking utilized within this study.

4 Experiment 1: Active Locomotion In-Vehicle and the Effects of Locomotion Method on its Experience (E1)

The first of the two experiments within our study focuses on evaluating the applicability of user-applied active locomotion in its baseline form. To assess how the dynamic environment of a moving vehicle influences active locomotion and the virtual experience, we performed evaluations in both a moving vehicle and stationary indoors setup. Additionally, we evaluated five locomotion methods that could be feasibly used in a constrained space, aiming to identify the most suitable method for in-car VR.

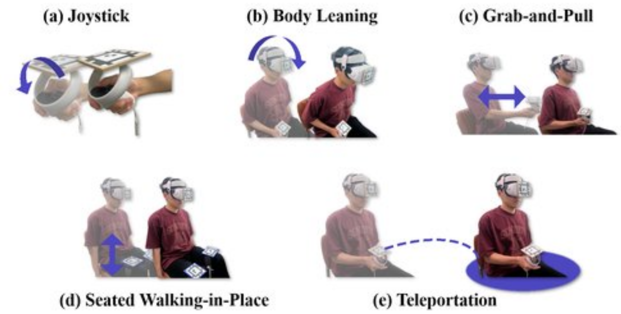


Figure 3: Visualization of the five locomotion methods implemented and evaluated for in-car VR use, consisting of: (a) Joystick, (b) Body Leaning, (c) Grab and Pull, (d) Seated Walking-in-Place, and (e) Teleportation.

4.1 Locomotion Methods

To evaluate how the experience of stationary locomotion methods change when utilized in-vehicle, five methods widely used in traditional VR were selected for the experiment, given their theoretical feasibility considering the constrained space of the passenger seat of a vehicle. Each method was implemented using the tracking capabilities of our in-vehicle setup and designed based on approaches from previous VR applications.

4.1.1 Joystick (J). The Joystick method was implemented using the thumb joystick on the Quest controller. The user can navigate the virtual environment by pushing the joystick in a desired direction, with sideways and diagonal movements possible as well [9, 19].

4.1.2 Body Leaning (BL). The Body Leaning method was implemented by tracking head pose via the fiducial marker attached to the forefront of the HMD. Upon initial calibration of the HMD's position at an upright posture, the user can lean their head or torso in any direction to move correspondingly in the virtual space, with speed proportional to the displacement vector's magnitude.

4.1.3 Grab and Pull (GAP). The Grab and Pull method was implemented by tracking the right controller's position, using the ceiling-mounted camera to detect the horizontal movement of the fiducial marker attached to the controller. When the user extends and then pulls the controller back while holding the index trigger, the XZ-axis displacement is translated into inverted motion within the virtual space.

4.1.4 Seated Walking-in-Place (SWIP). The Seated Walking-in-Place method is based on the design by Chan et al. [11], where the user lifts the forefoot of each foot to simulate walking or rotating within the virtual environment. To detect foot and leg movement, fiducial markers were affixed to each knee and tracked by the ceiling-mounted camera. Locomotion was implemented by translating the natural depth displacement of the knees that occurs when stepping in place. For consecutive steps, the user rotates in place in the corresponding direction, and for alternating steps, the user moves in the forward direction.

Figure 4: (a) Satellite mapping of the driving route used for the study, with designated acceleration profile visualized. (b) Conceptual mapping of the predetermined route, including fixed points of various driving events such as abrupt acceleration, deceleration and turning with specified velocities.

Figure 5: (a) Visualization of E1 procedure consisting of two sessions in a stationary indoors environment (left) and dynamic vehicle environment (right) respectively. (b) Depiction of the virtual environment used for E1, showing the coin collection task in which users participate in to initiate active locomotion.

4.1.5 Teleportation (T). Teleportation is triggered with the index trigger activating instant teleportation to the designated point visualized as a blue circle on the ground. Given that our setup allows only for positional tracking of the controller via an fiducial marker, we modified the standard raycasting algorithm for parabolic casting [67] so that users can control the destination point based only on the three-dimensional vector displacement of the controller.

4.2 Participants

A total of 20 participants (14 Male, 6 Female) were recruited for the within-subjects experiment, with ages ranging from 18 to 28 (M = 24.45, SD = 2.42). Of the participants, eighteen had varying degrees of experience in VR, with five having experience of over three years. Prior to the experiment, participants were administered the Motion Sickness Susceptibility Questionnaire Short (MSSQ-Short) to confirm their suitability for the experiment, with individuals scoring above 19 (the 75th percentile based on Golding et al.'s validation [33]) deemed ineligible for safety reasons, with all participants meeting the criteria. All experimental processes were approved by our Institutional Review Board.

4.3 Evaluation Setup and Procedure

The experiment was conducted in two different setups: a baseline stationary indoor environment and within a moving vehicle. The vehicle setup followed the specifications outlined in the Section 3.

For the in-car portion of the experiment, we selected a low-activity in-campus driving route, approximately 0.6 km in length and 3 minutes to traverse, with experiment times minimizing pedestrian/vehicle intervention. The route included various driving events recorded to have caused increase in motion sickness in previous in-car VR works [22, 43, 69], such as sudden accelerations, decelerations and turns, as shown in Figure 4. For the indoors environment, the duration of the virtual experience was measured to match that of the in-car setting. The length and duration of the route was chosen both from past works [22, 65, 79], and also through practical and safety-related precautions considering the within-subjects design and repeated exposure to both locomotion-induced and vehicle-induced motion sickness.

The virtual environment used was that of a wide forested area, where the user's primary task was to collect generated coins using a specified locomotion method, as shown in Figure 5-(b). The coin collection task is a commonly used technique in user studies to evaluate the usability of virtual locomotion [41, 45, 47, 55], incentivizing users to move freely within the virtual environment. When the user collects a coin by approaching it, another coin is generated in a randomized equidistant location. As some of the evaluated locomotion methods innately do not allow for full rotation, the coins were generated at angles within the field of view (approximately 85 degrees) of the user. The participants were required to keep collecting coins until the end of the driving route when in-car, or at the end of the set time corresponding to the route when indoors.

4.3.1 Measures. To evaluate the usability of active locomotion in different environments and with different locomotion methods, we employed relevant surveys related to motion sickness, presence, and perceived load. Given that virtual locomotion, particularly in a vehicular context, can introduce sensory mismatch and increase motion sickness, we used the Simulator Sickness Questionnaire (SSQ) as per past works [22, 43, 69, 84], selected for its suitability in holistically evaluating both VR-induced and vehicle-induced sickness symptoms such as nausea and disorientation [51]. Additionally, we used the Igroup Presence Questionnaire (IPQ) [94] to assess participants' sense of presence across three dimensions of involvement, spatial presence, and perceived realism. Presence is normally defined as the feeling of *being there* within the virtual environment and is a critical measure in accessing users' perception of a virtual experience [42, 100]. Finally, we used the NASA Task Load Index (NASA-TLX) [38] to measure participants' perceived load across six dimensions: mental demand, physical demand, temporal demand, performance satisfaction, effort, and frustration.

4.3.2 Procedure. Before the experiment, participants completed a demographic survey, then received instructions on the basic coin collection task, along with specific instructions on how to operate each of the five locomotion methods. A short practice session of up to 5 minutes was provided for participants to familiarize themselves with the controls of each method.

Participants experienced five conditions representing different locomotion methods in both the stationary and in-vehicle setups, with the car following the designated driving route in the latter. In cases of pedestrian intrusion that required significant deviation from the designated profile, we redid the condition. To control for auditory clues that may affect the user's perception of vehicle motion, the participants were equipped with noise-canceling earplugs. To account for long-term carryover effects and prevent environmental bias, we employed a within-subjects design, with the order of environments randomized across participants and locomotion methods counterbalanced within each environment using a balanced Latin square. The SSQ was administered twice per condition (immediately before and after experiencing the condition) to assess post-condition effects on the user [22], while the IPQ and NASA-TLX were administered after each condition. Once the surveys were finished, the participant was required to take the headset off and look out of the window while the car returned to the starting point, so as to alleviate motion sickness symptoms caused by the preceding condition. Before starting the next condition, participants were provided with a mandatory 10-minute rest period with additional time granted to participants upon request, to alleviate potential residual motion sickness and discomfort [30].

The duration of the experiment approximated to 1.5 hours per setting (<3 hours total), with the indoors and in-car setting proceeded in two separate but consecutive days. A 15-minute interview followed the experiment, where participants were asked to rank the five locomotion methods in order of overall preference in each environment, as well as provide answers to the following open-ended questions regarding the in-car experience:

- How did the experience of active locomotion in the in-car setting differ from that in the indoors setting?
- What were the positive and negative aspects of each method that influenced your preference ranking in each environment?
- During the overall experience, at what points did you feel interrupted or uncomfortable due to vehicle motion?

4.4 Results

To evaluate quantitative data from the experiment, we conducted a comprehensive statistical analysis using a repeated measures (RM) one-way ANOVA. We ensured that all measures met Kline's assumptions of normality with skewness below 3.0 and kurtosis below 10.0 [56], and validated sphericity through Mauchly's test. *Post hoc* comparisons within or between conditions were performed using paired samples t-tests with Bonferroni correction to assess significant differences between conditions. Additionally, ranked preferences for each condition were scored and averaged using the Borda count method to provide rank aggregation results [78].

4.4.1 Motion Sickness. Measures for motion sickness were analyzed using the total scores of the SSQ questionnaire, which were calculated by weighted sums of its subscales. An RM ANOVA was conducted on pre-condition measures across participants to assess consistency of residual sickness levels prior to each condition [22]. The results showed no significant variance between participants (Indoors: $F(4,76) = 0.508$, $p = 0.730$, $\eta_p^2 = 0.026$; In-Car: $F(4,76) = 0.025$, $p = 0.999$, $\eta_p^2 = 0.002$), confirming consistency across conditions.

Paired t-tests were performed to compare the pre- and post-condition SSQ results for each locomotion method to understand their effects on motion sickness through the duration of each experience, as shown in Figure 6. In the stationary indoors environment, significant increases in motion sickness were observed with Joystick ($t(19) = -2.523$, $^{*}p = 0.020$) and Grab-And-Pull ($t(19) = -2.772$, $^{*}p = 0.012$). In the dynamic in-car environment, significant increases were noted with Body Leaning ($t(19) = -4.445$, $^{***}p < 0.001$), Grab-And-Pull ($t(19) = -3.322$, $^{**}p = 0.003$), Seated Walking-in-Place ($t(19) = -2.769$, $^{*}p = 0.012$), and Teleportation ($t(19) = -2.101$, $^{*}p = 0.049$), while Joystick conversely showed no significant increase.

4.4.2 Presence. For the analysis of user presence felt while performing each locomotion method in each respective environment, we performed a one-way RM ANOVA between conditions for each environment and *post hoc* analysis for pairwise comparisons, with results shown in Figure 7. For the indoors environment, the results of the RM ANOVA showed high statistical significance ($F(4,76) = 7.989$, $^{***}p < 0.001$, $\eta_p^2 = 0.296$), with *post hoc* results showing significant difference between Joystick and Body Leaning ($^{***}p < 0.001$), Joystick and Grab and Pull ($^{**}p = 0.008$), and Body Leaning and Teleportation ($^{*}p = 0.032$). For the in-car environment, the results of the RM ANOVA showed high statistical significance as well ($^{**}F(4,76) = 3.933$, $p = 0.006$, $\eta_p^2 = 0.172$). Notably, *post hoc* analysis showed significant decrease for Teleportation compared to Body Leaning ($^{**}p = 0.009$) and Grab-and-Pull respectively ($^{***}p < 0.001$). A further analysis of the dimensions of IPQ scores show that involvement and spatial presence was heavily affected when indoors, with Joystick showing significantly lower scores compared to Body Leaning ($^{***}p < 0.001$, $^{***}p < 0.001$ respectively). However, when in-car, Teleportation showed lower scores in spatial presence compared to Grab-and-Pull ($^{*}p = 0.020$), and also in perceived realism compared to methods such as Joystick ($^{**}p = 0.008$) and Grab and Pull ($^{*}p = 0.019$).

4.4.3 Perceived Load. For in-depth analysis of perceived load, we examined the weighted results taken by combining raw and paired-choice data for each of the six dimensions of the NASA-TLX, with

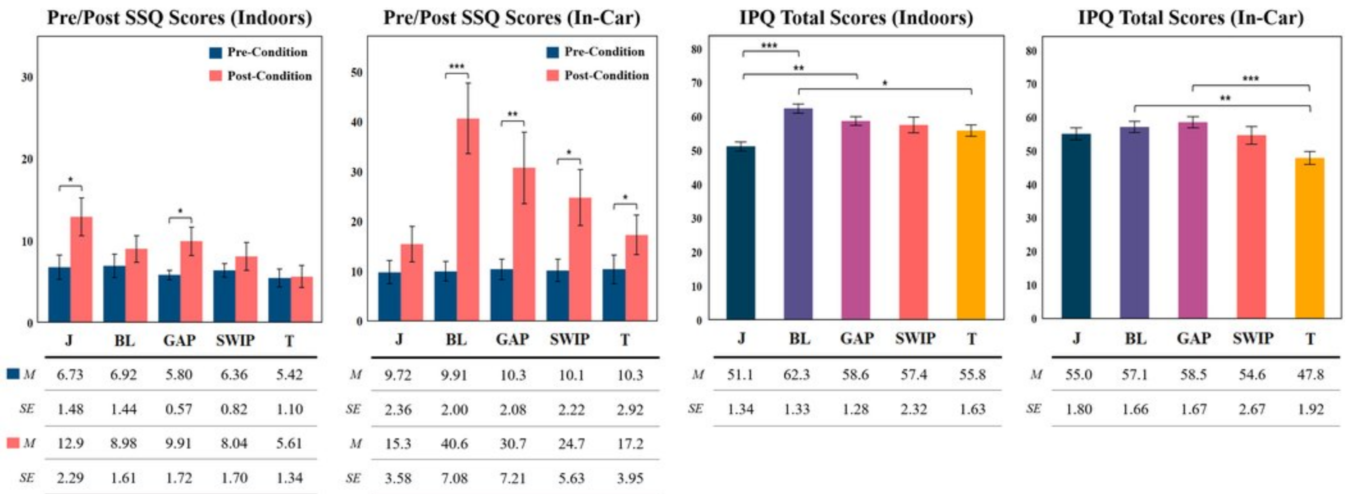


Figure 6: Results of pre- and post-condition SSQ scores (Left) and total IPQ scores (Right) in an indoors and in-car environment. The x-axis displays the five locomotion method conditions, and the y-axis represents calculated total SSQ or IPQ scores. Significance levels are indicated as $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

results shown in Figure 8. For the indoors environment, significant differences were found in the physical load dimension ($F(4,76) = 15.71$, $^{***}p < 0.001$, $\eta_p^2 = 0.453$), with *post hoc* analysis showing substantial differences between Joystick and Body Leaning ($^{***}p < 0.001$), Grab and Pull ($^{**}p = 0.002$) and Seated Walking-in-Place ($^{***}p < 0.001$), and also between Teleportation and Grab and Pull ($^{*}p = 0.035$) and Seated Walking-in-Place ($^{**}p = 0.002$). Additional yet less substantial differences were found in the Performance and Effort dimensions as well, with Joystick notably showing lower effort than all other methods excluding Teleportation. In the in-car environment, similar results were found in terms of physical load ($F(4,76) = 17.17$, $^{***}p < 0.001$, $\eta_p^2 = 0.474$), with both Joystick and Teleportation having substantially lower scores than the remaining three methods. Additionally, Joystick showed significantly lower effort compared to Body Leaning ($^{**}p = 0.001$) and Seated Walking-in-Place ($^{*}p = 0.021$) in the in-car environment.

4.4.4 Preference. The preference rankings provided by participants for the five locomotion methods in each environment were counted and translated via Borda Count, where each ith-ranked option ($i = 1, ..., n$) within n conditions was assigned $n - i$ points [93], with results shown in Figure 8. In the indoors environment, Body Leaning emerged as the most preferred locomotion method, receiving 53 points, followed by Teleportation (45 points), Seated Walking-in-Place (42 points), Grab-and-Pull (33 points), and Joystick (27 points). Conversely, in the in-car environment, the rankings shifted considerably, with Joystick becoming the most preferred method (53 points), followed by Teleportation (47 points), Grab-and-Pull (36 points), Body Leaning (35 points), and Seated Walking-in-Place (29 points). Notably, Joystick was the most preferred method in-car, in contrast with being the least preferred indoors.

4.4.5 Interviews. The post-experiment interviews were focused mainly on the active locomotion experience within the in-car environment, and rating each locomotion method either in of itself or compared to its experience in the stationary environment. The resulting responses correlated closely with the preference ratings and survey data, further confirming the user experience felt for each locomotion condition and also for the in-car VR active locomotion experience overall.

The Joystick method, which received the highest preference rating, also had the most positive responses (26 comments) and least negative responses (10 comments) in subsequent interviews. Most users focused on its intuitiveness and ease of control (P1,2,4-7,8,10,11,13-16,18) as well as its low physical load, with participants stating that the low physical load made it suitable for a dynamic car environment (P5,7-10,16,20). Some participants also noted that the continuous nature of the Joystick method seemed to match the continuous movement of the real car, as opposed to discrete methods such as Teleportation (P1,3,5,18,19). Negative responses included loss of embodiment compared to the other methods (P1,2,6,12,17) and relatively low variability in speed (P3,11,20).

The Teleportation method also received more positive than negative responses, with its ease of use and effectiveness (P2,3,5,7,8,11,18), as well as its low levels of motion sickness (P6,8,10) being the major aspects of positive feedback. However, participants also felt that the method made it feel like the virtual world wasn't real (P5,9,10,13-15) due to its unrealistic manner of locomotion, and also felt a high level of spatial disorientation (P1,10,15,20) and physical load (P4). Additionally, some participants specified that while motion sickness was not felt during the stationary setting, the perceived conflict between the discontinuous nature of Teleportation and the continuous motion of the vehicle actually led to more motion sickness than other methods (P12,15,19).

The remaining three methods (Grab-and-Pull, Seated Walking-in-Place, Body Leaning) all received more negative than positive comments in terms of its usability within a moving car. High physical load was a common factor between the three conditions (P2,5-7,9,11,13,14,17-19), particularly for Body Leaning where participants

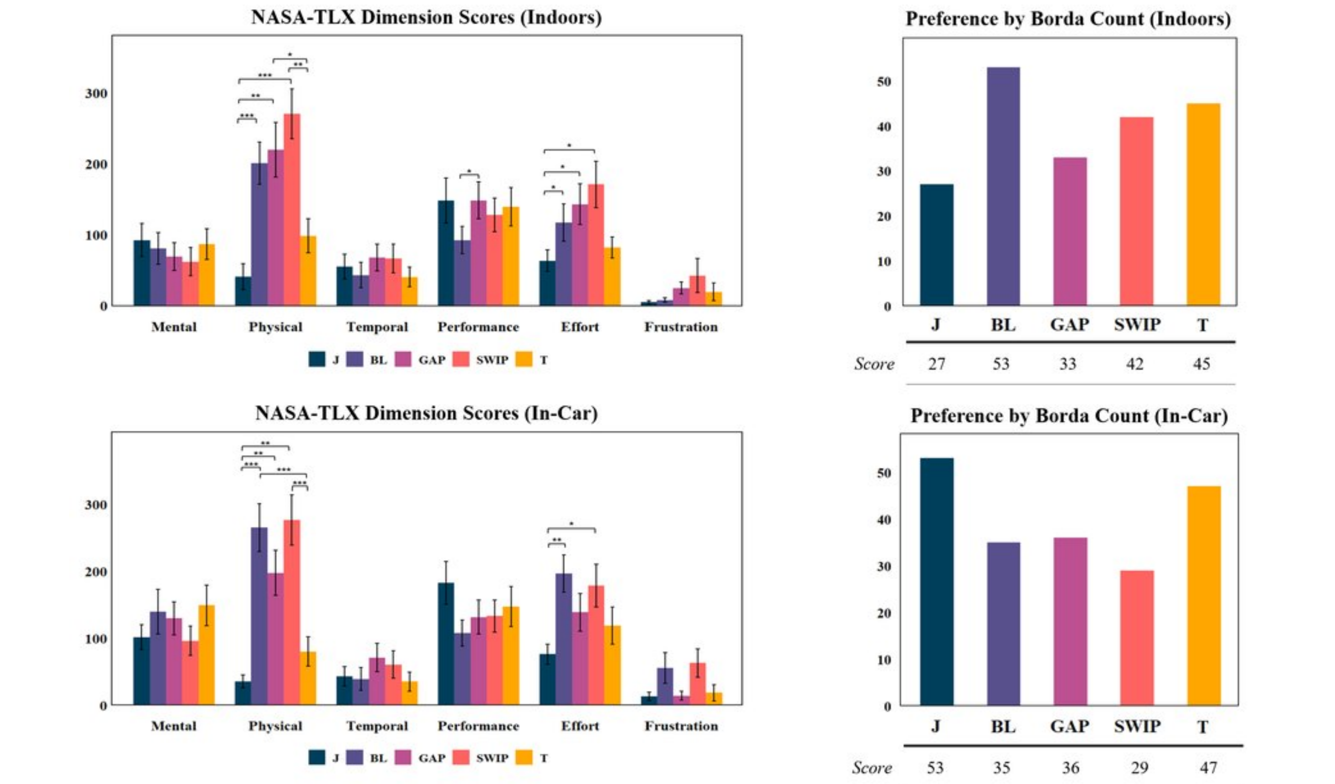


Figure 7: (Left) Results of NASA-TLX by each dimension in each respective environment. The x-axis displays the six dimensions of the NASA-TLX with comparisons between the five locomotion methods, and the y-axis represents weighted scores for each dimension. Significance levels are indicated as $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. (Right) Results of the accumulated preference scores by Borda count in each respective environment. Higher scores indicate higher preference among the participants.

felt that the motion of the vehicle made the virtual locomotion difficult to control (P1,2,4-7,9,11,14,19). Other comments included feeling that the walking method didn't feel natural within the dynamic environment for Seated Walking-in-Place (P1,4,9,12,16,19) and feeling high levels of discomfort due to postural instability for Body Leaning (4,7-9,17-19).

Interruptions in User Experience: Regarding the overall active locomotion experience in the moving car relative to in a stationary indoors environment, all participants save one (P8) mentioned that the bodily sensation of the motion of the car affected the experience negatively. Particular instances in which participants felt that user experience was severely harmed included when they felt the vehicle turning left or right (P1-7,9,10,12-18,20), suddenly decelerating (P1-7,10-16,18-20), accelerating (P2,3,5,7,9,12-16,18), and due to various small bumps in the road (P9,15,16). Several participants also mentioned that these changes in vehicle movement were especially interrupting for locomotion methods that required more body movement, such as Body Leaning (P1,2,4-7,9,11,14,19), Grab-and-Pull (P8,9,11,19), and Seated Walking-in-Place (P4,9,11,19).

4.4.6 Going into E2. From the discussed results of the quantitative and qualitative data collected in the experiment, along with the reported preference rankings, Joystick stands out as a suitable locomotion method in in-car VR in the current setup. By process of elimination, Body Leaning, Grab-and-Pull and Seated Walking-in-Place was rejected due to their negative affects shown in the correlated measures of motion sickness and perceived physical load, as well as their reported unsuitability in a dynamically moving environment. Of the two remaining methods, measures and interview feedback indicated a preference for Joystick as opposed to Teleportation in terms of motion sickness and presence, especially in the context of the moving vehicle and its perceived alignment with virtual locomotion. Therefore, we proceeded with Joystick as the method of locomotion in the procedure of E2.

Improving the Active Locomotion Experience: While the results of the pilot study showed the potential applicability of in-car active locomotion in its baseline form, especially when using the Joystick method, participants still reported room for improvement in terms of user experience as well as motion sickness. Participants generally reported feeling a higher level of motion sickness when operating in-vehicle, as opposed to indoors. In particular, situations in which the vehicle dynamically changes, such as accelerating or turning, proved to negatively affect not only the locomotion task, but also the virtual experience as a whole. The primary reason for this, from previous references and the results of E1, are related to the sensory mismatch that occurs between the visual sense within the virtual world, and the vestibular and kinesthetic sense affected by the vehicle's movements [22, 43, 69]. Thus, we felt it imperative to explore methods in which the virtual contents can be manipulated to reflect sensory alignment between the real vehicle's movement and the virtual environment, *without* restricting the freedom of active locomotion. From the instances in which participants of E1 reported an increase in sensory mismatch, we aimed to target specific points of acceleration, deceleration, and turning in E2 as the primary driving events in which contextual cues can be applied to enhance the in-car active locomotion experience.

5 Design of Cues Contextualizing the Physical Motion of the Vehicle

5.1 Focus Group Interview

Methods for translating the somatosensory sensations caused by vehicle movement, other than visual 1:1 mapping of vehicle motion, remain relatively unexplored in the current research field. Even with some solutions related to minimizing sensory mismatch in previous studies [22, 83, 87, 88], none have been specifically designed or implemented for the purpose of active locomotion in-vehicle. To address these research gaps in the design process, we conducted a Focus Group Interview (FGI) with academic researchers in VR and HCI from our institute to explore the design of contextual cues that minimize sensory mismatch without restricting virtual locomotion. Seven participants (four male, three female) were recruited, aged 25 to 34 (M = 27.57, SD = 3.02), with a combined 37 years of experience in VR content design and HCI research, and 21 years of experience specifically in in-car VR research.

The interview was conducted in a two-hour session. After the moderator introduced the research background and Experiment 1 findings in a 20-minute overview, participants spent 20 minutes developing ideas for contextual cues to enhance the in-car VR experience with minimal impact on active locomotion, ranging from general theories for mitigating sensory mismatch (e.g., visual distraction) to specific cue designs (e.g., visualizing wind). Then proceeded a round-robin presentation of ideas, followed by open discussion for refining or creating new designs.

From the session, a total of 10 concepts and 22 specific designs were presented and recorded. We then conducted a dedicated convergence session to refine these ideas, focusing on rejecting, reformulating, or reclassifying them into a manageable number of contextual cue designs for evaluation in our user study. Criteria in selection included flexibility to address various driving events causing sensory mismatch (e.g., accelerations, decelerations, and turns), seamless integration into the virtual environment without extensive hardware, minimal interference with user navigation, and theoretical soundness supported by logical or prior research findings.

Based on these criteria, we finalized four specific designs for implementation in our study. The specific implementations within the virtual contents in our study are summarized below and in Figure 9, as well as the underlying concepts that we hypothesized to potentially improve the in-car active locomotion experience.

5.1.1 Tilting Ground (TG). The first developed method, termed *Tilting Ground*, involves slanting the ground in the virtual scene toward the direction of the inertial forces generated by the vehicle's movements, visualizing the source of perceived gravitational force (g-force). For example, when the vehicle accelerates, the virtual ground tilts backward, creating an uphill visual cue. By adjusting the virtual ground's inclination in response to these forces, this method not only contextualizes the kinesthetic sensation of acceleration, simulating the illusion of directional gravitational pull, but also synchronizes the resulting shift in the user's posture. The implementation in our study targets changes in vehicle movements in the following manner: the virtual ground tilts up when the car accelerates, tilts down when the car decelerates, and tilts left or right when the car makes a right or left turn respectively.

5.1.2 Movement Inducement (MI). The second method, termed *Movement Inducement*, differs from other approaches by actively encouraging the user's bodily motion to align with the postural shifts caused by vehicle acceleration. A similar concept had been partially incorporated by the work of Elsharkawy et al. [22], where virtual elements drew the user's attention upward in synchronization with vehicle acceleration. By prompting users to physically respond to virtual stimuli in congruence with external forces, this method has the potential to enhance the sense of control, improve sensory feedback coherence, and reduce the risk of motion sickness [22, 85]. In our user study, we implemented interactions that required users to avoid various traps using upper body or head movement within the virtual environment, designed to correspond with specific driving events. During sudden acceleration, a large axe swings in front of the user, prompting them to lean back to avoid it. Conversely, during deceleration, a descending wall from the ceiling requires the user to lean forward and duck to avoid collision. In turning scenarios, spears fly toward the user, with slight directional shifts that induce the user to lean left or right depending on the direction of the turn. The timing and duration of these interactions were mapped to be congruent with the postural shifts that naturally occur during the linear and angular accelerations of the vehicle.

5.1.3 Force Transfer (FT). The third method, *Force Transfer*, inspired by the concept of stretch mapping [102], focuses on translating the forces caused by linear or angular acceleration to a different source of force that can reasonably be perceived within the virtual environment. While *Tilting Ground* more closely maps the accelerations felt from vehicle movement into directional g-force, *Force Transfer* translates these forces to other sources of potential force in the virtual environment, so as to contextualize real-world sensations to provide a more non-invasive integration. In our study, we expressed the vehicle-caused forces in the virtual environment as visualized wind, with directions correlating to the inertial forces felt during acceleration, deceleration, and turning events. This wind is both directly visualized as directional shifts in fog particles, as well as indirectly represented through the after-effects on various objects to effectively increase immersion [102].

5.1.4 Visual Distraction (VD). The final method, *Visual Distraction*, is derived from previous research that highlights the use of visual distractions in VR as an effective strategy for reducing motion sickness symptoms [80, 105]. This approach manipulates the sensory load of the user by focusing it on the visual sense, thereby reducing the cognitive perception of changes in vestibular or kinesthetic sensations caused by vehicle movement. We integrated this approach

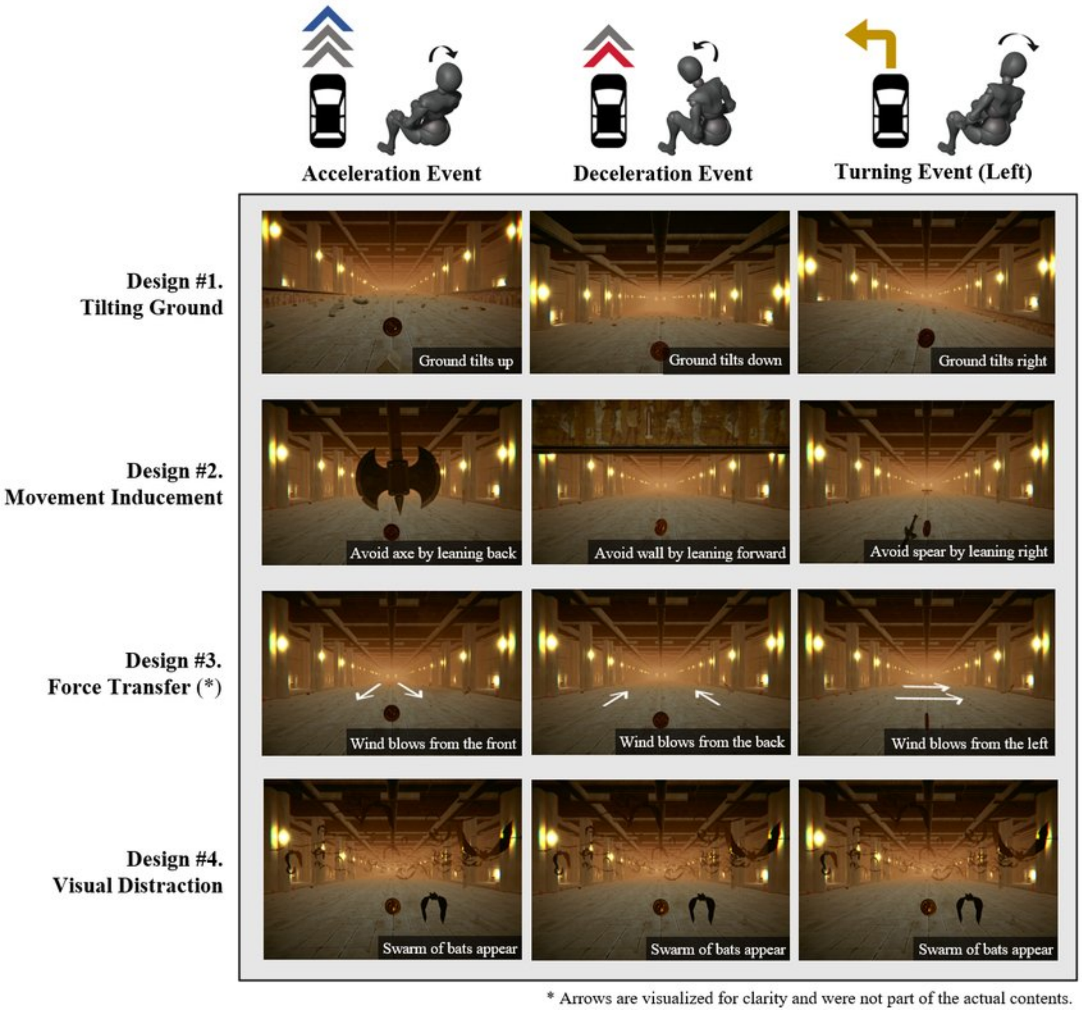


Figure 8: Tabular representation of the designed contextual cues finalized to implement and evaluate in E2. Columns represent the specific driving events that each cue targets along with an illustration of the natural posture shift of the user caused from each event, and rows represent the designed contextual cues that aim to mitigate sensory mismatch within each driving event.

by incorporating visually complex components into the virtual environment, specifically during driving events where sensory mismatch increases [49]. Within our contents, we implemented this as a swarm of bats encompassing the virtual environment at moments of acceleration, deceleration, or turning. To differentiate from other methods, which all include elements of visual distraction to an extent, we increased the complexity of the visual cue through a greater number of visual objects and randomizing direction to prevent bias regarding virtual self-motion or perceived force.

6 Experiment 2: Examining the Effects of Contextual Cues on the Experience of Active Locomotion in In-Car VR (E2)

The primary goal of E2 was to assess how the active locomotion experience is affected by each of the four designed contextual cues. We evaluated factors such as motion sickness, presence and perceived load, along with participants' subjective opinions regarding the benefits and drawbacks of each tested cue, while also comparing with a baseline condition in which no cue was applied.

6.1 Participants

A group of 20 participants (13 Male, 7 Female) was recruited for the experiment, with ages ranging from 19 to 35 (M = 24.8, SD = 3.11), with 18 of these participants having participated in E1. Of these participants, 16 had varying levels of experience with VR, and five had experience in VR usage spanning over three years. Before the experiment, participants completed the MSSQ to assess their suitability for the study, with individuals who scored above the 75th percentile deemed ineligible due to safety reasons. All participants included in the data collection met the criteria. Experiment procedures were approved by our Institutional Review Board.

6.2 Evaluation Setup and Procedure

E2 was designed to investigate the effectiveness of various contextual cues in enhancing the user's experience during active locomotion within an in-car VR environment. This experiment focused on assessing how these cues could reduce sensory mismatch and improve presence compared to the baseline, with the locomotion method standardized to the Joystick method as confirmed from the results of E1.

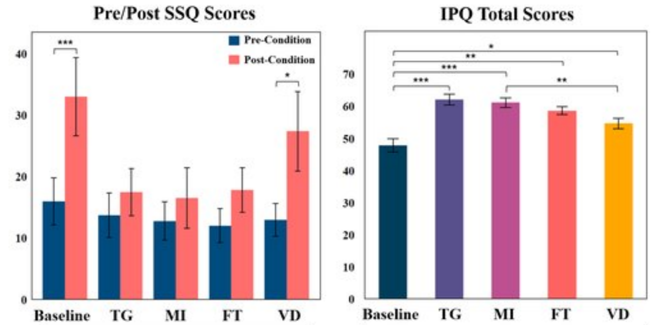
Participants were placed in a virtual environment themed as an ancient temple as shown in Figure 9, to allow for the seamless integration of the four contextual cues. The same coin collection task and driving route from E1 (shown in Figure 4) were utilized to measure the impact of the contextual cues applied in the various driving events that harmed the active locomotion experience.

6.2.1 Measures. As in E1, the SSQ was administered before and after each condition to assess symptoms of motion sickness, including nausea, oculomotor issues, and disorientation. The IPQ was used to measure the participants' sense of presence within the virtual environment, focusing on dimensions such as spatial presence, engagement, and realism. Furthermore, the NASA-TLX evaluated the perceived load during each condition, especially in regards to how each contextual cue affected both the locomotion task and the virtual experience as a whole.

6.2.2 Procedure. Participants began the experiment by completing a demographic survey and receiving brief instructions on the coin collection task and the contextual cues they would encounter during each condition of the experiment. Unlike E1, no separate practice session was provided, as the Joystick locomotion method required minimal familiarization, and to prevent any preliminary bias regarding each of the contextual cue conditions.

Participants experienced the five conditions, consisting of the baseline and four contextual cues, with order randomized via balanced latin square. Excluding the baseline condition where no cues were applied, each of the four contextual cues were activated in response to the predefined entry points of the driving events in the driving route, such as acceleration, deceleration, and turns. While the vehicle moved along the driving route, the participants navigated the virtual environment using the Joystick method to collect coins that randomly appeared equidistant in the environment. The SSQ was administered both before and after conditions, while the IPQ and NASA-TLX surveys were administered after each condition to provide quantitative data regarding their experience. As with E1, participants were given a mandatory 10-minute rest period between conditions, with the option for additional time if requested.

Following the completion of all conditions, participants were asked to rank their preferences regarding the contextual cues at the end of the experiment, including the baseline condition. The experiment concluded with a brief interview, where participants were asked to provide qualitative feedback on the effectiveness of the contextual cues in reducing motion sickness and enhancing presence, as well as any positive or negative feedback regarding their experience. Excluding interviews, The experiment lasted approximately 1.5 hours per participant.



	Baseline	TG	MI	FT	VD
Pre *M*	15.9	13.7	12.7	12.0	12.9
SE	3.82	3.59	3.10	2.79	2.65
Post *M*	32.9	17.4	16.5	17.8	27.3
SE	6.37	3.83	4.90	3.62	6.48

	Baseline	TG	MI	FT	VD
M	47.8	62.0	61.0	58.6	54.6
SE	2.07	1.72	1.51	1.26	1.57

Figure 9: Results of pre- and post-condition SSQ scores (Above) as well as IPQ total scores (Below) for E2. The x-axis displays the five conditions in which contextual cues were applied (or not applied), and the y-axis represents calculated total SSQ scores and IPQ scores respectively. Significance levels are indicated as $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

6.3 Results

The analysis for the results of E2 followed the approach used in E1. We confirmed that all measures met the normality assumptions, with skewness below 3.0 and kurtosis below 10.0, and verified sphericity using Mauchly's test. Significant differences between conditions were identified using repeated measures one-way ANOVA (RM ANOVA), followed by Bonferroni-corrected *post hoc* tests where appropriate. Participants' preferences were ranked using the Borda count method. Along with qualitative insights from post-experiment interviews, these results highlight the role of contextual cues in shaping the in-car active locomotion experience.

6.3.1 Motion Sickness and Presence. Motion sickness was assessed using the total scores from the SSQ questionnaire as shown in Figure 10, calculated by summing its three subscales with weighted contributions. An RM ANOVA of pre-condition measures across participants confirmed the consistency of residual motion sickness levels before each condition, with no significant variance detected ($F(4,76) = 0.384$, $p = 0.819$, $\eta_p^2 = 0.020$). Paired t-tests comparing pre- and post-condition SSQ scores revealed significant increases in motion sickness for the baseline condition ($t(19) = -3.531$, $^{***}p < 0.001$) and *Visual Distraction* ($t(19) = -2.143$, $^{*}p = 0.045$) respectively. In contrast, no significant increases were observed in the other three conditions which incorporated contextual cues.

The analysis of presence, indicated significant differences across conditions ($F(4,76) = 15.38$, $^{***}p < 0.001$, $\eta_p^2 = 0.447$). As can be seen in Figure 10, *post hoc* analysis identified the baseline condition as having significantly lower presence scores compared to all other conditions, as seen in comparisons with *Tilting Ground* ($^{***}p < 0.001$), *Movement Inducement* ($^{***}p < 0.001$), *Force Transfer* ($^{**}p = 0.005$), and *Visual Distraction* ($^{*}p = 0.015$). Additionally, *Visual Distraction* scored significantly lower than *Movement Inducement*

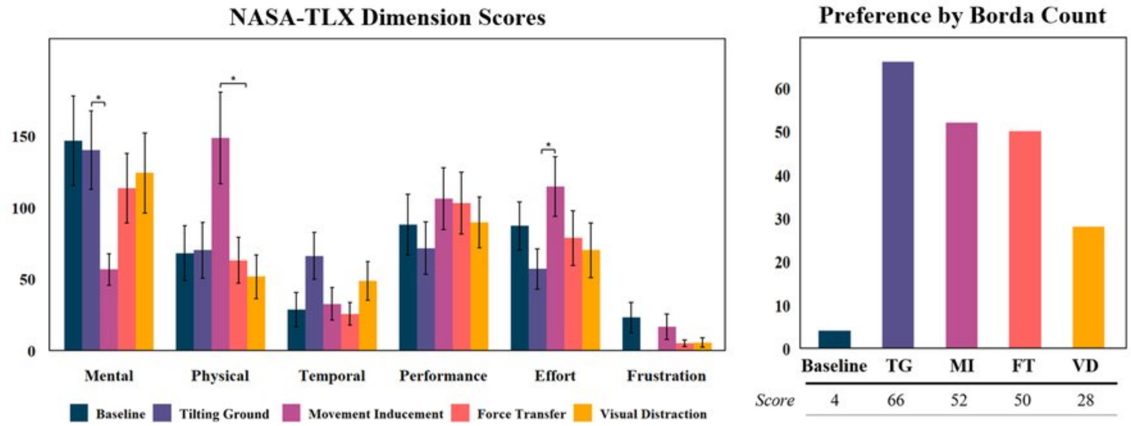


Figure 10: (Left) Results of the NASA-TLX by each dimension for E2. The x-axis displays the six dimensions of the NASA-TLX with comparisons between the five conditions, and the y-axis represents weighted scores for each dimension. Significance levels are indicated as $^{*}p < 0.05$. (Right) Results of the accumulated preference scores by Borda count. Higher scores indicate higher preference among the participants.

($^{**}p = 0.002$) as well. Analyses of the IPQ's dimensions yield further insights, with all conditions save *Visual Distraction* showing significantly higher involvement ($^{***}p < 0.001$, $^{***}p < 0.001$, $^{*}p = 0.036$ for *Tilting Ground*, *Movement Inducement* and *Force Transfer*) and spatial presence ($^{*}p = 0.011$, $^{**}p < 0.002$, $^{*}p = 0.017$ for *Tilting Ground*, *Movement Inducement* and *Force Transfer*) compared to the baseline, but no significance in terms of perceived realism.

6.3.2 Perceived Load and Preference. Perceived load was assessed across six dimensions of the NASA-TLX, with results for weighted scores within each dimension depicted in Figure 11. *Post hoc* results show higher levels of load for *Movement Inducement* compared to *Visual Distraction* in terms of effort ($^{*}p = 0.028$), as well as compared to *Tilting Ground* in terms of physical load ($^{*}p = 0.024$).

Participants' preference rankings were aggregated using the Borda count method, as shown in Figure 11. The Tilting Ground condition emerged as the most preferred, accumulating 66 points, followed by Movement Inducement with 52 points, Force Transfer with 50 points, and Visual Distraction with 28 points. The baseline condition received the fewest points, totaling 4.

6.3.3 Interviews. The post-experiment interview was centered around the participants' perception of the various applied contextual cues and their effects on user experience during the active locomotion experience. Interview data was categorized as positive and negative feedback, as shown in Table 1.

Tilting Ground: The Tilting Ground condition was generally well-received by participants, with many noting that the alignment of the tilting ground with the perceived direction of forces significantly mitigated sensory mismatch (P1,2,5-8,10,13-16,18), compared to the other cues. Moreover, the realistic portrayal of gravity and the movement of objects within the environment was appreciated for enhancing the immersive quality of the VR experience (P4,11,12,19,20). However, some participants felt that the tilting of the ground detracted from the realism of the overall virtual experience (P3,13,17), particularly when perceived to not match the vehicle's actual motion (P13,17). Additionally, a few participants suggested that a more natural feeling could be induced if their movement was affected by the tilting effects, such as moving slower when going uphill (P3,19).

Movement Inducement: The Movement Inducement condition garnered mixed responses. On the positive side, many participants found the condition to be highly immersive due to the active involvement required, which made the experience more engaging and interactive (P1,2,4,6,16,18). This active engagement was also noted to reduce motion sickness compared to the baseline, as actively performing tasks distracted from sensory conflicts (P1,3-5,7,8,11-13). However, some participants expressed concerns about the coordination required between physical actions and the VR environment, particularly when the vehicle's movement clashed with their intended movements, causing discomfort (P9,10,14,20). In addition, the effort associated with avoiding obstacles while still maintaining the locomotion task was overwhelming for some (P9,14,15,19). Furthermore, the sense of agency was diminished for some participants, as the required movements felt forced by the physical forces from the vehicle, rather than voluntary (P9,14,17).

Force Transfer: The Force Transfer condition was appreciated for its clarity of directional cues, which helped contextualize the physical forces felt from the vehicle's movements (P1-3,5,8,11,12,15,16,18,20). Others also mentioned an added sense of speed and dynamism to the VR environment (P1,8,12). However, some participants pointed out that the wind effect lacked variability and felt too consistent, which sometimes led to a mismatch between the expected and actual physical sensations, causing minor sensory conflict (P4,9,10,13). Additionally, the lack of physical sensation accompanying the visual wind effect reduced the overall sense of immersion for some, as the wind felt disconnected from the VR environment (P10,14,17,19).

Visual Distraction: The Visual Distraction condition, featuring bats as a distraction, received divided feedback. Some participants found the visual distraction effective in mitigating motion sickness by diverting their attention away from potential sensory conflict (P3,6,14,19). However, many participants felt that the bats were the least effective in mitigating sensory mismatch, as the distraction was not strong enough to counteract the physical sensations experienced during vehicle movement (P1,4,7,8,10-13,16-18.20). Over time, the bats became more of a visual nuisance to some, with their repetitive nature leading to diminished effectiveness and increased visual clutter (P7,9,12,16,17).

7 Discussion

To examine the feasibility of active locomotion in in-car VR, we proceeded in a comprehensive two-step study examining the effects of locomotion method and presence of contextual cues within the virtual contents respectively. Through the analysis of quantitative results and user feedback from both experiments, we discuss the insights earned within each study, as well as go through a set of design considerations for potential expansions of utilizing active locomotion.

7.1 Regarding Comparison of Locomotion Methods

An analysis of user experience factors for active locomotion in in-car VR versus a stationary environment highlights how the dynamic nature of vehicle movement affects each locomotion method's feasibility. For motion sickness, participants in a stationary environment reported higher sickness with Joystick compared to embodied methods like Body Leaning, Seated Walking-in-Place, and discontinuous methods like Teleportation [19, 57], which aligns with results from previous research in indoors scenarios. However, results for the in-car conditions showed inverse trends: methods requiring embodied movement, such as Body Leaning, Grab-and-Pull, and Seated Walking-in-Place, notably increased motion sickness, likely due to interference from the vehicle's motion, causing postural instability and a perceived loss of control [5, 12, 21, 64, 101]. The Joystick method, requiring only thumb movement, was less affected by these external forces, while Teleportation was similarly effective due to its intermittence in terms of virtual motion. Another notable distinction when in-vehicle is the perception of sensory alignment that participants felt for linear and continuous locomotion as opposed to discontinuous methods, which could explain the increase in motion sickness for Teleportation as opposed to Joystick, the latter of which provides the sensation of constant acceleration and thus mitigates motion sickness more effectively, regardless of direction.

Presence levels also shifted between environments. In a stationary setting, Body Leaning offered higher presence than Joystick, due to aligned proprioceptive and visual feedback [99, 104]. However, in-car presence decreased for Body Leaning, reportedly due to the clash of active leaning for locomotion and vehicle-induced posture sway from accelerations. Presence for Teleportation dropped further due to its discontinuous nature and subsequent mismatch with physical sensations of vehicle motion [1, 4], while results remained stable for Joystick as participants perceived a coherence between virtual movement and the vehicle's continuous motion.

For perceived load, physical effort was a key differentiator across methods. In both environments, Joystick and Teleportation—requiring minimal physical exertion—were preferred over more demanding methods like Body Leaning, Grab-and-Pull, and Seated Walking-in-Place [9, 14]. When in-car, physical load had a reported greater impact, correlating negatively with user preference as vehicle forces increased strain, challenging users' ability to maintain virtual locomotion. The weight of the VR headset (>0.5kg) may also have had a role in increased physical load for embodied methods such as Body Leaning in-car, due to the postural shifts from the vehicle's accelerations. Joystick's higher performance and lower perceived effort reinforce the challenges of embodied locomotion in moving vehicles, where users favored lower-strain options.

Overall, the turbulent nature of in-vehicle environments was shown to affect the usability of various virtual locomotion methods in a multitude of factors, leading to significant changes in user preference (such as Joystick becoming least preferred to most preferred when in-car). These results highlight the importance of further exploring in-car-specific guidelines for virtual locomotion, rather than relying on those designed for stationary or indoor environments.

7.2 Regarding Evaluation of Applied Contextual Cues

Results for E2 indicate that contextual cues such as *Tilting Ground* and *Force Transfer* effectively reduce motion sickness by addressing sensory mismatches, expanding on prior studies which emphasize congruence of motion to reduce sickness in VR [22, 43, 69, 71]. Unlike traditional approaches that match virtual and vehicle motion, these cues re-contextualize inertial forces, thereby mitigating sickness without exact motion synchronization [3, 89, 90]. Although *Tilting Ground* was predicted to be especially effective due to its alignment of inertial and gravitational forces, it showed comparable effectiveness to other cues, suggesting flexibility in perceived motion integration for sickness mitigation. Engagement also seemed to influence motion sickness mitigation: *Movement Inducement*, which encourages user participation by shifting posture against vehicle motion, reduced sickness through active engagement, consistent with studies on motion sickness reduction through user engagement [22, 85, 106]. However, *Visual Distraction* proved least effective, likely due to its lack of contextual adaptation to directional vehicle accelerations.

Presence was similarly enhanced by all cues, though *Visual Distraction* had a lesser effect, underscoring the importance of synchronized sensory inputs for immersive presence [49, 83, 110]. However, interview responses highlighted limitations for each cue: *Tilting Ground* lacked natural environmental transitions, and *Force Transfer* lacked expected stimuli, suggesting improvements in sensory feedback could further enhance presence [22, 83]. Perceived load was highest for *Movement Inducement*, as participants struggled with unassisted timing of body movements against vehicle motion. This cue's physical demands reflect its design, where movement timing depends on the user rather than synchronized content, suggesting that continuous, rhythm-based challenges could improve alignment with vehicle-induced sway.

These results reveal the impact of each contextual cue on the in-car VR experience, particularly in correlation to its preference rankings. *Tilting Ground* was most favored for its natural alignment of vehicle acceleration with gravitational force, while limitations in *Movement Inducement* and *Force Transfer* point to areas for refinement, such as timing and feedback. The lower ranking of *Visual Distraction* suggests that reducing sensory mismatch requires deeper, synchronized interactions rather than simple visual cues. These insights highlight the need to tailor contextual cues to the unique sensory dynamics of in-car VR, guiding future design improvements.

7.3 Future Design Considerations

The ideal in-car locomotion method should maintain a balance between ease of use and embodiment: Of the five locomotion methods we tested in E1, Joystick emerged as the most preferred by participants, where users seemed to prioritize its minimal physical exertion and effectiveness in turbulent environments over other conditions. However, the Joystick method is not without its innate flaws, chiefly in regards to the lack of embodiment within the virtual environment, leading to potential negative effects in motion sickness and immersion. Other methods of locomotion may be implemented or developed that introduces elements of embodiment while still being applicable in-vehicle in terms of physical strain, such as finger-walking [50, 54] or arm-swinging [77, 111]. Alternatively, integrating the real car's motion within a technique, such as turning with a joystick but allowing for forward motion via an engage trigger, can also be a viable method to increase sensory alignment in the context of virtual vehicle manipulation.

Alternative transitions between active/passive locomotion can be employed within the virtual contents: In our study, we prioritized active locomotion independent of the vehicle's movement. However, during the progress of the study, we also alternatively explored potential combinations of active and passive locomotion that might help mitigate motion sickness while maintaining a degree of navigational freedom. For example, passive locomotion could be synchronized with specific driving events, such as turns or acceleration, where sensory mismatch is most pronounced, while active locomotion could be employed in more stable situations such as uniform speed. Another idea involves allowing users to intermittently select a virtual destination, with the system automatically aligning the route to match the vehicle's actual movements or subtly redirecting the path. While these concepts are beyond the scope of our study, they offer interesting avenues for future research on integrating active locomotion within in-car VR environments.

Cues should effectively contextualize car movements while maintaining flexibility in content design: A key factor in the design of contextual cues is its flexibility of integration into different virtual environments. Among the evaluated contextual cues, *Visual Distraction* offers the most design freedom, as it does not rely on directional cues. *Force Transfer* and *Movement Inducement* are also relatively flexible, allowing designers to choose which virtual forces or motion-inducing components correspond to the inertial forces experienced by the user. In contrast, *Tilting Ground* is more rigid, requiring specific conditions in the virtual environment for seamless implementation. Notably, our findings indicated that more rigid methods were more effective in improving the experience, implying an inverse relationship between design flexibility and cue effectiveness. Future research should aim to develop contextual cues that maintain balance between these factors, ensuring both high usability and adaptability in varied virtual scenarios.

Continuous application of contextual cues can be an alternative to discrete implementation: For our study, we treated driving events like turning and acceleration as discrete instances for implementing contextual cues, which offers flexibility in choosing when and where to integrate these elements. However, another effective implementation could involve continuously applying cues to reflect ongoing changes in the car's linear and angular acceleration. To take example from our developed cues, *Tilting Ground* could be sustained continuously to match the vehicle's forces, or the level of distraction in *Visual Distraction* may be dynamically adjusted to concurrently match the vehicle's acceleration. Importantly, discrete and continuous contextual cues need not be mutually exclusive; they can be provided in combination, with discrete cues targeting key vulnerability scenarios while continuous cues promote an ambient awareness of the vehicle's motion and intentions.

8 Conclusion and Future Works

Our study explored the potential of active locomotion in in-car VR environments, focusing on the challenges and solutions associated with maintaining presence and minimizing motion sickness. We evaluated various active locomotion methods applied in-car as opposed to a stationary indoors setting to examine the changes in usability due to its dynamic environment. Among the five locomotion methods tested, Joystick emerged as the most suitable in terms of overall user experience, with its advantages in effective use with minimal physical interventions while maintaining levels of motion sickness and presence. Additionally, to further improve the in-car VR active locomotion experience, we designed and evaluated a set of contextual cue methods which aimed to minimize sensory mismatch. Methods such as directly visualizing the physical forces caused by the vehicle by tilting the virtual ground, translating vehicle-caused forces to other virtual sources of perceived force such as wind, or inducing the user to change their posture in alignment with vehicle motion showed significant improvements through decreased motion sickness and increased presence.

Through future works, we plan to address the limitations of our study and expand upon our initial findings regarding active locomotion in in-car VR. Our study was proceeded in a relatively short and constrained driving setup (3-minute duration, 0.6 km route with six acceleration events and four turning events). Therefore, we aim to improve the scalability of our findings through examining long-term effects and boundaries across longer, more varied scenarios such as in highways or urban traffic. Additionally, we plan to examine the feasibility of more complex virtual locomotion such as substantial rotations and movement opposite the vehicle trajectory. Evaluating performance measures of in-car locomotion methods in the context of different navigation-oriented tasks (e.g. entertainment/productivity, speed/precision) is also necessary to assess their suitability for various applications. While this study focused on the effects of vehicle movements related to linear and angular acceleration, future research could develop contextual cues for other motion sickness-inducing events, such as vertical displacements caused by speed bumps or rough terrain [49, 69]. Also, while we selected Joystick as the preferred locomotion method in our second experiment, further studies could explore the impact of contextual cues on other locomotion methods to provide a more comprehensive understanding of their compatibility. Finally, while our current work focused on visual cues integrated into virtual content, future research could explore the potential of multisensory contextual cues such as by haptic feedback through Galvanic Vestibular Stimulation (GVS) [10, 47, 69] or Electrical Muscle Stimulation (EMS) [22, 46, 48], to further minimize sensory mismatch and enhance the in-car VR active locomotion experience.

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A IPQ Dimension Results

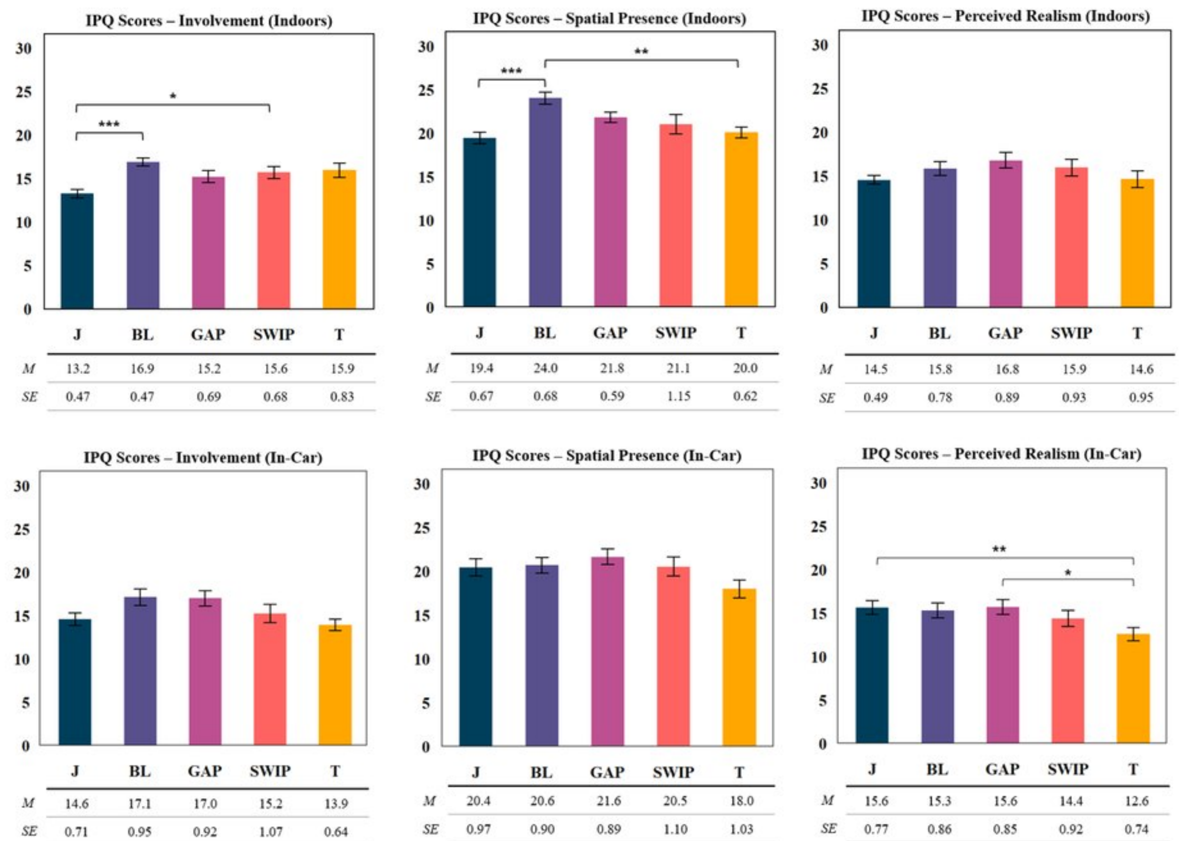

Figure 11: Results of the IPQ subscores for E1 (indoors and in-car respectively). The x-axis displays the five locomotion method conditions, and the y-axis represents subscores from each dimension. Significance levels are indicated as $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

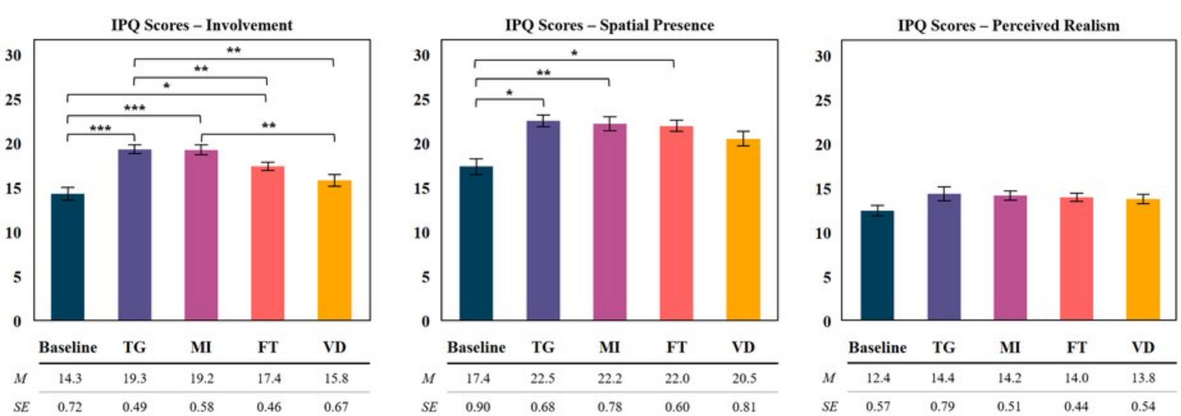

Figure 12: Results of the IPQ subscores in each environment for E2. The x-axis displays the five locomotion method conditions, and the y-axis represents subscores from each dimension. Significance levels are indicated as $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.