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Towards Non-Disruptive Visual Motion Cues that Balance Motion Sickness against Distraction for Passenger VR

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Submitted in fulfilment of the requirements for the
Degree of Doctor of Philosophy

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Abstract

Using Virtual Reality (VR) technology in moving vehicles holds great potential to enhance the passenger experience and support innovative Non-Driving Related Tasks (NDRTs). However, VR usage in vehicles presents significant challenges due to motion sickness. This condition often arises from a sensory mismatch between visually perceived motion and the vestibular system's input. This problem is especially pronounced when passengers engage with immersive VR environments while in transit as the VR visual cues are often in contradiction to vestibular cues. Consequently, current VR experiences tend to rely on matched motion cues, meaning experiences where the virtual movements mirror the real movements of the vehicle. While matched visual motion cues that align with optic flow can effectively reduce sensory conflict and mitigate motion sickness, they often impose constraints that may distract users from their primary tasks in VR. Moreover, the requirement for matched cues significantly limits design flexibility, constraining the diversity of VR scene designs. To address these issues, this thesis investigates alternative visual cue designs that move beyond the traditional approach of the VR scene matching visual motion. These novel cues reduce motion sickness by minimizing sensory mismatch without replicating optic flow, thereby reducing distraction and enabling non-disruptive visual motion cues. This thesis addresses two primary types of vehicle motion: rotational and linear. In terms of rotational motion, innovative cues were validated through four studies, ranging from implicitly manipulating the movements of existing virtual interfaces to explicitly presenting virtual objects that react to the forces experienced by the vehicle. For linear motion, visual cues that represent vehicle accelerations rather than velocity changes (as used in traditional matched-motion cues) were tested in two studies in real driving environments. By comparing user motion sickness ratings and distraction levels with those of solutions commonly used in the field, these designs demonstrated their ability to strike a balance between mitigating motion sickness and minimizing distraction from NDRTs. This thesis contributes novel insights into how visual motion perception, beyond simple matched motion cues, can improve passenger VR experience without inducing motion sickness. By strategically designing to reduce the motion sickness associated with VR use and integrating VR devices into vehicles, this research also underscores the importance of minimally distracting cues to enhance the overall user experience, which will become a vital component of future vehicles interactions.

Contents

Abstract	i
Acknowledgements	x
Declaration	xi
1 Introduction	1
1.1 Motivation	1
1.2 Research Questions	4
1.3 Thesis Statement	4
1.4 Thesis Outline	5
2 Literature Review	6
2.1 Introduction	6
2.2 Motion Sickness	6
2.2.1 Theories of Motion Sickness	7
2.2.2 Relationship Between Motion Sickness, Simulator Sickness and Cyber-sickness	8
2.2.3 Measures of Motion Sickness	10
2.2.4 Individual Differences in the Experience of Motion Sickness	12
2.3 Future Passenger Experience	13
2.3.1 The Development and Future of Autonomous Vehicles	14
2.3.2 Challenges and Design Opportunities in Future Passenger Experiences .	16
2.3.3 Virtual Reality in Future Passenger Experience	17
2.4 Motion Sickness Mitigations	20
2.4.1 Motion Sickness Mitigations: Vehicle-Centric Design	20
2.4.2 Motion Sickness Mitigations: Passenger-Centric Sensory Cues	22
2.5 Distraction and Its Measurement	28
2.5.1 Definition of Distraction	28
2.5.2 Measuring Distraction: No Unified Standard	29

3	Exploration of Visual Cues for Rotational Motion: Implicit Cues	31
3.1	Introduction	31
3.2	Study 1: Preliminary Exploration of the Effectiveness of Rotating Display Cues	33
3.2.1	Study Setup	33
3.2.2	Study Platform	33
3.2.3	Measurement Method	34
3.2.4	Visual Cues Design	36
3.2.5	Study Procedure	37
3.2.6	Results	38
3.2.7	Study 1 Discussion	40
3.3	Study 2: Validation of Rotating Display Cues	41
3.3.1	Study Platform	42
3.3.2	Measurement Method	42
3.3.3	Study Procedure	43
3.3.4	Participants	43
3.3.5	Results	43
3.4	Limitations	46
3.5	Overall Discussion	46
4	Exploration of Visual Cues for Rotational Motion: Explicitly Cues	48
4.1	Introduction	48
4.2	Study 3 - Efficacy of Physics-Based Cues	50
4.2.1	Study Design	50
4.2.2	Study Platform	51
4.2.3	Measurement Method	52
4.2.4	Participants	53
4.2.5	Study Procedure	54
4.2.6	Results	54
4.2.7	Discussion	55
4.3	Study 4 - Comparing Physics-Based Cues with Others	56
4.3.1	Study Platform	56
4.3.2	Measurement Method	56
4.3.3	Study 4 Design	57
4.3.4	Participants	59
4.3.5	Study Procedure	59
4.3.6	Results	59
4.3.7	Study 4 Discussion	61
4.4	Limitations	62
4.5	General Discussion	63

4.5.1	Efficacy of Physics-based Cues in Motion Sickness Mitigation	63
4.5.2	Physics-based Cues Mitigate Motion Sickness whilst Minimizing Dis- ruption	63
4.5.3	Integrating Visual Cues in VR to Enhance Motion Perception and Re- duce Motion Sickness	63
5	Exploration of Visual Cues for Linear Motion	65
5.1	Introduction	65
5.2	Study 5 - Efficacy of Velocity and Acceleration-Based Cues	68
5.2.1	Study Design and Setup	68
5.2.2	Experimental Platform	70
5.2.3	Driving Route	71
5.2.4	Measurements	72
5.2.5	Participants	73
5.2.6	Study Procedure	73
5.2.7	Results	74
5.2.8	Study 5 Discussion	75
5.3	Study 6 - Exploring Larger Acceleration Cue Coefficients	76
5.3.1	Study Design and Setup	77
5.3.2	Experimental Platform	79
5.3.3	Driving Route	79
5.3.4	Measures	80
5.3.5	Participants	81
5.3.6	Results	81
5.3.7	Study 6 Discussion	85
5.4	Limitations	86
5.4.1	Route and Driving Conditions	86
5.4.2	Driving Conditions	86
5.4.3	Tasks	86
5.4.4	Distraction Measurement	87
5.4.5	Lack of a Baseline Condition on Motion Sickness	87
5.5	General Discussion	87
5.5.1	The Similar Effects of Acceleration and Velocity Cues on Motion Sickness	88
5.5.2	Velocity-based Cues Introduce Greater Distraction and Reduced Focus Compared with Acceleration-based Cues	88
5.5.3	No Evidenced Benefits of Gain for Acceleration Cue Design	89
6	Conclusion	90
6.1	Introduction	90

6.2	Research Questions	91
6.2.1	Research Question 1	91
6.2.2	Research Question 2	93
6.2.3	Research Question 3	94
6.3	Future Applications	96
6.3.1	Low-Distraction / Minimally Disruptive Visual Cues in Future Passenger VR Applications	96
6.3.2	Using Extended/Mixed/Augmented Reality Devices to Deliver Generalised Spatial Motion Cues	96
6.3.3	Towards Novel Multimodal Motion Cue Designs	97
6.4	Contributions and Recommendations	97
6.4.1	Thesis Contributions	97
6.4.2	Design Recommendations	98
6.5	Limitations	100
6.5.1	The Integration of Multiple Cues	100
6.5.2	Classification of Vehicle Motion	100
6.5.3	Limitations of the Motion Simulation platform	101
6.5.4	Overall Low Levels of Motion Sickness	101
6.5.5	Limitations of VR Task Simulations	101
6.6	Conclusion	102

List of Tables

2.1	Distinguishing motion sickness (MS), simulator sickness (SS), and cybersickness (CS).	9
2.2	Symptoms and Their Severity Levels in Simulator Sickness Questionnaire . . .	12
2.3	Comparison of automation levels in vehicle technology based on SAE level . .	15
2.4	Visual Cues Design Categories Based on Classification [39]	22
3.1	Motion sickness slider measurement and description.	36
6.1	Comparison of Three Visual Cue Designs	95

List of Figures

2.1	Transparent wall design: Visual motion is observed through the transparent wall in the background. Image adapted from [20].	23
2.2	Two examples of visual cues involve moving or rotating the entire visual content. In these cases, the lateral movement or rotation of the entire NDRT interface is used as a visual cue. Adapted from [39].	25
2.3	Pseudo-acceleration stimulus for reflected movement against the curved acceleration from the front view. Image adapted from [151].	26
3.1	Examples of 2D virtual displays in VR. From left: Virtual Desktop [46], Multi-screens [132]	32
3.2	On the left is the <i>RotoVR</i> rotating chair. On the right is a participant undergoing rotational motions on the chair.	34
3.3	A screenshot is shown, which mirrors the participant's visual display. The display presents a maths question, a red dot for the attention task, and a slider to allow the participant to indicate their real-time level of motion sickness.	35
3.4	A top-down view of the visual cue movement. The shaded areas represents the VR field of view, and the red line depicts the top-down view of the 2D task plane. The user is at the centre, sat on the <i>RotoVR</i> rotating chair. In the case shown on the right, the coefficient X was set to 0.3, with both the participant and <i>RotoVR</i> rotated 90° to the right. As a result, the red task plane was rotated 63° ($90 - 90 \times 0.3$) to the right. In the case shown on the left, the coefficient X was set to 0.6, so the task plane was only rotated 36° ($90 - 90 \times 0.6$).	38
3.5	The Nausea related symptoms subscale from the SSQ. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median. There was a significant difference between the Control and 0.3 conditions.	39
3.6	Study 2, building on improvements from Study 1, featured conditions with longer durations and larger intervals.	41
3.7	Value of the real-time motion sickness slider for the two conditions. The shaded area represents the corresponding confidence interval.	44

3.8	The total SSQ scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median. Lower SSQ scores indicate reduced levels of motion sickness.	45
4.1	An example of fuzzy dice hanging in a vehicle. The way they sway with the physical movement of the vehicle provided design inspiration. Image cited from [120]	49
4.2	Participant's visual experience. The screen presents a mathematics question along with multi-choice answers and a slider for the participant to indicate their current level of motion sickness in real-time. Three red spheres, which form the visual cue, are placed directly behind the VR task area. Their swaying motion constitutes the visual cues.	51
4.3	A participant engages in rotational movements while seated in the <i>RotoVR</i> chair.	52
4.4	Motion sickness value. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.	55
4.5	Total SSQ scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.	56
4.6	On the left is the experimental design for the Direction-based cue condition. On the right is the design for the Speed-and-direction-based cue. Motion information is conveyed through the rotation of the background.	58
4.7	Development of motion sickness over time for the 3 conditions rated via the slider displayed in the headset. Shaded areas represent 90% confidence intervals. Y-axis represents Motion Sickness Slider values, participants were able to rate their level of motion sickness: 0: "no problems", 1: "some discomfort", 2-5: "vague to severe dizziness", 6: "little nauseated", 7: "mild nauseated".	60
4.8	Total SSQ scores of study 2, The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.	61
4.9	Distraction ranking frequencies across conditions (n = 17). Bars show how many participants placed each condition 1st/2nd/3rd (Rank 1 = least distracting; Rank 3 = most distracting).	62
5.1	On the side are screenshots of what the participant sees, with the left portion representing the Velocity/Control condition. The background of the former will move with the velocity of the vehicle, while the background of the latter is static. The right portion shows the starfield used in the Acceleration condition. The size and position of the task plane remained constant across conditions, though differences in VR screenshots may arise from varying angles or vehicle motion.	68

5.2	The motion patterns of the starfield are displayed in animated form. On the left, as the vehicle accelerates, the starfield moves backward (opposite to the direction of the user's forward view); in the middle, as the vehicle moves at a constant speed, the starfield remains static; on the right, as the vehicle decelerates, the starfield moves forward.	69
5.3	The participant is shown wearing a VR headset while seated in the vehicle for the experiment. On the left side of the image, an experimenter is present to assist the participants.	70
5.4	The schematic of the PassengXR Open-Source Motion Platform is composed of multiple parts; for this experiment, only the functions of the ESP32 and OBD units were utilized.	71
5.5	Road taken during Studies 1 and 2. The red line indicates the straight road used in Study 1. The blue line represents the additional curves near the starting and ending points of the route, which were included in Study 2. The red dot is the start point of studies	72
5.6	The MISC maximum value. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median. Lower MISC scores indicate reduced levels of motion sickness.	75
5.7	The total SSQ scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median. Lower SSQ scores indicate reduced levels of motion sickness.	76
5.8	The experimental vehicle is travelling on the public road.	79
5.9	The MISC maximum value. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.	82
5.10	The total SSQ scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.	83
5.11	The video tasks accuracy rates. A higher accuracy rate indicates greater comprehension of the video contents.	84
5.12	Participants' subjective focus ratings, with 0 representing extremely low focus and 10 representing extremely high focus.	85

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Declaration

The research presented in this thesis is entirely the author's own work. Parts of the thesis are based on the author's previously published papers, with appropriate modifications and extensions. Specifically:

- **Study 1 in Chapter 3** has been published at AutomotiveUI '22:

Zhanyan Qiu, Mark McGill, Katharina Margareta Theresa Pöhlmann, and Stephen Anthony Brewster: *Display Rotation for Reducing Motion Sickness Caused by Using VR in Vehicles*. In *Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '22)*, Association for Computing Machinery, New York, NY, USA, 25–29. DOI: <https://doi.org/10.1145/3544999.3552489>

- **Study 2 in Chapter 3** has been published at AutomotiveUI '23:

Zhanyan Qiu, Mark McGill, Katharina Margareta Theresa Pöhlmann, and Stephen Anthony Brewster: *Manipulating the Orientation of Planar 2D Content in VR as an Implicit Visual Cue for Mitigating Passenger Motion Sickness*. In *Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '23)*, Association for Computing Machinery, New York, NY, USA, 1–10. DOI: <https://doi.org/10.1145/3580585.3607157>

- **Study 3 and Study 4 in Chapter 4** have been published at SUI '24:

Zhanyan Qiu, Mark McGill, Katharina Margareta Theresa Pöhlmann, and Stephen Anthony Brewster: *Augmenting Virtual Spatial UIs with Physics- and Direction-Based Visual Motion Cues to Non-Disruptively Mitigate Motion Sickness*. In *Proceedings of the 2024 ACM Symposium on Spatial User Interaction (SUI '24)*, Association for Computing Machinery, New York, NY, USA, Article 24, 1–10. DOI: <https://doi.org/10.1145/3677386.3682079>

- **Study 5 in Chapter 5** has been published at AutomotiveUI '24:

Zhanyan Qiu, Mark McGill, Katharina Margareta Theresa Pöhlmann, and Stephen Anthony Brewster: *Acceleration instead of Speed: Acceleration Visual Cues in VR for Reduced Motion Sickness in Linear Motion*. In *Adjunct Proceedings of the 16th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '24)*, Association for Computing Machinery, New York, NY, USA, 56–61.

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- **Study 6 in Chapter 6** has been submitted and is currently under review.

Chapter 1

Introduction

1.1 Motivation

With the arrival of autonomous driving technologies, many drivers will become passengers and are expected to experience long-distance travel more frequently [27, 54, 110]. This transformation underscores the significance of Non-Driving Related Tasks (NDRTs), encompassing activities such as reading, watching movies, and working, in shaping the future passenger experience. Cutting-edge computing platforms [1] like Virtual Reality (VR) devices such as the Meta Quest 3 and Pico 4, have the potential to revolutionize our interaction with digital content, thereby significantly enhancing the passenger experience. These displays are digital interfaces that users can configure within a 3D space to optimize size and spatial orientation, accommodating individual ergonomic preferences and improving overall visual comfort. Consequently, these virtual displays enhance existing in-vehicle screens [107, 112]. This innovation holds substantial promise for transforming passenger entertainment and productivity experiences, facilitating non-driving related tasks (NDRTs) like streaming videos, browsing social media, and remote work, significantly enriching the passenger’s travel experience. These NDRTs are currently delivered mainly through 2D planar productivity applications (e.g. word processors, web browsers, *Virtual Desktops*) and entertainment content (e.g. television, movies), providing novel modes of interaction.

Despite the advances in VR technology, motion sickness remains a significant challenge during travel [27]. This impacts the overall experience of passengers during their journeys and potentially hinders the realization of innovative VR travel experiences. The prevailing theory posits that motion sickness is primarily caused by a sensory conflict between expected and experienced vestibular and visual self-motion [144]. When passengers are in motion, their vestibular system receives information related to the vehicle’s physical movement, while their visual system receives conflicting information, such as the vehicle’s static interior or movement from information displayed on screens within the vehicle. The use of VR headsets can further contribute to this conflict by partially or completely occluding the outside visual world. This conflict impedes the further application of VR technology in transportation.

However, with thoughtful design, VR headsets also hold substantial promise as tools to mitigate motion sickness [138, 141]. VR headsets could present visual or multimodal information (e.g. auditory) about the outside world to help resolve this sensory mismatch [144, 190] and be used as a tool for motion sickness mitigation. For example, visual stimuli, such as displaying optic flow patterns conveying motion information from the external environment in the virtual background, which are able to reduce conflicts between sensory systems and enhance passenger situational awareness [109]. Additionally, VR headsets can "manipulate" or correct passenger head position and movement by ensuring they maintain an upright posture, by positioning visual content in a way that encourages them to look up and avoid mis-alignment with gravity [52], and guiding their head tilt/rotation. Based on sensory conflict theory [77, 124], using *matched motion*, which accurately replicates the vehicle's movements—such as speed and rotation—within VR scenes, ensures passengers have a consistent perception of their self-motion. This has proven effective in reducing the incidence of motion sickness as confirmed by various studies: [19, 20, 61, 109, 111, 135, 138].

While *matched motion* can mitigate motion sickness, cues might detract from the overall user experience by diverting attention and causing distraction from the media content or NDRT the passenger is trying to use [109, 136, 188]. In psychological studies on distraction, it is typically defined as the factors that interfere with an individual's ability to complete a primary task [148]. This interference can arise from multitasking or external stimuli [163]. In highly immersive VR single-task studies, users' sensory input is confined to the visual elements within the virtual interface, making any non-task-related visual stimuli potentially disrupting, referred to as visual interference [163]. *Matched motion* involves providing visual motion cues that mimic the visual signals passengers would experience throughout their journey. In real-world driving scenarios, such as navigating city streets or highways, the vehicle undergoes substantial motion, including acceleration, deceleration, cruise, and turns, meaning the user sees many matched motion cues, which can be distracting. Cues are typically presented as starfield displays or cityscapes [122, 138, 139, 183], in the VR environment. These cues match the visual motion that would be perceived if there was no obstruction by VR headset or the car interior. They are often unrelated to the primary entertainment or productivity task, they occupy a significant portion of the visual field and they continuously change with the vehicle's movement. The motion of the visual cues also generates substantial optic flow information. This could capture user attention and introduce distractions, and limits the design space for in-car VR as the whole background is take up by the cues. On the other hand, in the absence of this additional information, motion sickness could greatly hinder individuals from enjoying their travel experiences and risk rejection of passenger VR. This motivates the need for *minimally-disruptive motion cues* that are less distracting and more integrated into the scene or content being experienced, to reduce impact on user experience whilst retaining mitigation efficacy. This also underscores that the question of how best to visually convey vehicle motion (vestibular perceived self-motion) in VR to reduce

motion sickness remains unclear. A range of new ways is needed by which self-motion can be non-disruptively integrated into VR experiences and alongside NDRTs, ultimately supporting more productive travel.

Vehicles primarily experience linear and yaw (rotation) motion on the road [115]. Hence, research in this thesis targets these types of motion separately, resolving sensory mismatch by conveying congruent visual cues based on sensed vehicle motion. The designs proposed are intended to reduce visual distraction and the impact of the virtual motion cues.

For yaw motion, Studies 1 and 2 demonstrated that altering the orientation of 2D planar content in VR devices based on the orientation of a motion simulator significantly reduced motion sickness. This indirect method of conveying matched motion information is identified as a form of implicit motion cue. Given that engaging with 2D content such as videos, web browsing, and reading is likely to remain prevalent in vehicle-based VR scenarios, integrating implicit motion cues into existing planar interfaces represents a promising direction for enhancing passenger comfort. However, this design does not meet the needs of scenarios where users require a fixed interface for NDRTs. To address this, the next stage of research focused on preserving a fixed NDRT interface while embedding motion cues within the background, preferably by subtly utilizing existing background elements. Study 3 explored whether incorporating physics-based movements of virtual objects within the VR scene could further mitigate motion sickness. The results confirmed that visual dynamics reflecting external vehicle movements effectively serve as visual cues, validating the utility of physics-based approaches. In Study 4, these physics-based cues were compared to conventional matched motion cues and directional arrow cues. The findings indicated that, while physics-based cues achieved comparable reductions in motion sickness relative to traditional matched motion cues, they resulted in significantly lower perceived distraction.

For linear motion, novel acceleration-based visual cues were specifically developed to accommodate the vestibular system's heightened sensitivity to changes in velocity. Two real-world, on-road studies were conducted to evaluate their efficacy. Study 5 validated that these acceleration-based cues significantly reduced motion sickness. Study 6 further confirmed that the benefits of acceleration-based cues were comparable to traditional matched motion cues, while inducing minimal distraction to Non-Driving Related Tasks. Additionally, this study validated the effectiveness of visual cue gain design in enhancing user experience.

Across both rotational and linear vehicle motions, this thesis demonstrates that various low-optic-flow visual cue designs can effectively reduce motion sickness while significantly minimizing distraction. These findings open up new opportunities for developing innovative motion-sickness mitigation strategies and stimulate further exploration into how visual cues can alleviate sensory mismatches. This thesis argues that the future of in-car VR experiences lies in breaking free from the need for matched motion visual cues and moving towards complementary cues that mitigate sensory conflict and maximize passengers' ability to engage in VR-based NDRTs.

1.2 Research Questions

The main research questions for this thesis are:

- **RQ1:** For rotational motion, how is the trade-off between motion sickness and distraction impacted by visual cues that resolve sensory mismatch?
 - **RQ1.1** What are the effects of using implicit cues that manipulate the movements of 2D planar virtual interfaces?
 - **RQ1.2** What are the effects of using explicit physics-based cues presenting virtual objects that react to the forces experienced by the vehicle?
- **RQ2:** For linear motion, how is the trade-off between motion sickness and distraction impacted by visual cues that resolve sensory mismatch?
 - **RQ2.1** Can acceleration-based visual cues reduce motion sickness?
 - **RQ2.2** How does the trade-off between motion sickness and distraction compare between existing velocity-based matched motion cues and acceleration-based cues?
 - **RQ2.3** Can tuning the parameters of acceleration-based visual cues benefit user experience?
- **RQ3:** How to achieve minimally disruptive visual motion cues that balance motion sickness against distraction for Passenger VR?

1.3 Thesis Statement

This thesis investigates how innovative visual cues within VR environments can effectively mitigate motion sickness while minimizing distraction during NDRTs when passengers are in motion. Current approaches, such as *matched motion* cues, reduce motion sickness but introduce significant visual distraction, detracting from the overall passenger experience. To address this challenge, this research explores novel *minimally-disruptive motion cues* tailored specifically to linear and rotational vehicle motions, integrating subtle yet effective motion representations into VR scenes. By comparing these designs against existing methods through real-road studies, the thesis identifies visual cue strategies that optimally balance the reduction of motion sickness with minimal interference to user attention, and provides practical design principles to deepen theoretical understanding, supporting the broader adoption of VR in transportation contexts.

1.4 Thesis Outline

Chapter 2: Literature Review This chapter reviews research areas that inform the future of passenger VR experiences, particularly focusing on the challenges posed by motion sickness. It provides a detailed review and investigation of the literature related to motion sickness and methods for VR mitigation techniques. The review concludes by highlighting some of the distractions caused by existing mitigation techniques.

Chapter 3: Exploration of Visual Cues for Rotational Motion: Implicit Cues This chapter contains two lab studies conducted using a 1 DoF yaw rotation motion simulator that explore visual cue-based strategies for alleviating motion sickness induced by rotational movement. These studies investigate the trade-off between motion sickness and distraction when resolving sensory mismatches through implicit visual cues. These implicit cues convey motion information indirectly based on existing VR UIs. The experiment compared the results of motion sickness measurements with control conditions, demonstrating the potential of unconventional new visual cues.

Chapter 4: Exploration of Visual Cues for Rotational Motion: Explicit Cues This chapter contains two further lab studies using the same setup as the previous chapter. It explores explicit cues that react to physical motion. The effectiveness of these physically-based cues is examined. Comparisons with commonly used designs demonstrate their potential in mitigating motion sickness and reducing distractions. The research conducted in Chapter 3 and Chapter 4 provide answers to **RQ1** and offer insights into **RQ3**.

Chapter 5: Exploration of Visual Cues for Linear Motion: Acceleration Cues This chapter includes two studies conducted in real vehicles to explore visual cue-based strategies for mitigating motion sickness under linear motion. Starting from the limitations of commonly used solutions, which can distract attention, this research proposes and evaluates an alternative: acceleration-based visual motion cues. These studies demonstrate that acceleration-based cues are as effective as matched motion cues in preventing motion sickness while being minimally disruptive to non-driving related tasks. The studies also adjust various parameters to provide references for more personalized future mitigation solutions. This chapter provides answers to **RQ2** and **RQ3**.

Chapter 6: Conclusions Here, the work conducted is summarized and the answers to the research questions presented. It also highlights thesis's key contributions, limitations and suggests directions for design guidelines and future research.

Chapter 2

Literature Review

2.1 Introduction

This literature review provides a comprehensive synthesis of existing work at the intersection of motion sickness research, VR design, and in-vehicle passenger experience.

The first section outlines the theoretical foundations of motion sickness, including the major explanatory models. It also discusses the conceptual overlap between motion sickness and cybersickness, and reviews widely used measurement tools. Additionally, individual differences in susceptibility to motion sickness are examined, shedding light on the diversity of user responses to similar stimuli.

The second section shifts focus to the future of passenger experience in autonomous vehicles. It highlights how the development of AVs opens up new possibilities for productivity and entertainment, with VR playing a central role in enhancing passenger engagement. At the same time, it identifies emerging challenges in designing for comfort, safety, and usability in such environments. These challenges introduce new design constraints and open up opportunities for innovation in motion cue delivery and in-vehicle interaction.

The third section provides an in-depth review of motion sickness mitigation strategies, particularly those involving visual cues. Mitigation techniques are categorized into vehicle-centric approaches and passenger-centric designs. Special attention is given to cue designs within VR contexts, including both matched and semi-matched motion cues.

Finally, the review turns to the concept of distraction—an increasingly issue in VR visual cues. The literature is reviewed with regard to how distraction is defined, what measurement metrics are used, and how task design influences user attention.

2.2 Motion Sickness

Motion sickness, a condition affecting countless individuals across diverse environments, has intrigued humans for centuries, with historical records dating back to 800 BC [64]. Symptoms

significantly impacting an individual's ability to function and enjoy certain activities or environments. Despite its widespread occurrence, the exact physiological mechanisms underlying motion sickness remain not fully understood.

2.2.1 Theories of Motion Sickness

Motion sickness is a complex phenomenon with underlying causes that remain incompletely understood within the scientific community. Prominent explanatory frameworks, including Sensory Conflict Theory [145] and Postural Instability Theory [146], offer valuable insights but also face notable critiques and limitations.

The Sensory Conflict Theory, proposed by Reason and Brand [145], remains the most widely cited explanation. This theory posits that motion sickness results from discrepancies among visual, vestibular, and proprioceptive sensory inputs. Specifically, the visual system perceives motion through tracking movements, light variations, or parallax effects; the vestibular system detects self-motion via the balance organs in the inner ear; and the proprioceptive system gathers information regarding bodily posture and movements through sensors in muscles, tendons, and joints. According to this theory, motion sickness arises from conflicts between expected and actual sensory inputs during motion [10]. Such conflicts occur when the brain encounters difficulties reconciling differing sensory signals, triggering symptoms of motion sickness.

Additionally, Sensory Conflict Theory addresses discrepancies between anticipated sensory feedback, shaped by prior experiences, and actual sensory information received during movement [180]. This phenomenon is notably exemplified among experienced operators. For instance, seasoned pilots have developed consistent sensory expectations related to physical accelerations and positional changes during real flights. However, in fixed-base flight simulators lacking realistic force feedback, significant deviations occur between expected and actual sensory inputs, potentially making experienced pilots more susceptible to simulator-induced motion sickness than novices [95].

Sensory Conflict Theory effectively explains motion sickness across diverse contexts, including traditional vehicular motion (e.g., cars and ships) and virtual environments, making it one of the most widely referenced theories in motion sickness research.

Although the Sensory Conflict Theory has substantial support [77], it is not without criticism. Riccio and Stoffregen [146] argue that the theory does not universally predict its occurrence. This critique highlights the need for more nuanced models that can account for a broader range of motion-related experiences. They introduced the Postural Instability Theory [146], suggesting that motion sickness arises from prolonged postural instability. According to this model, any condition leading to sustained instability of the body or its parts could provoke symptoms of motion sickness. This instability disrupts an individual's natural postural, affecting their ability to maintain balance and understand their centre of gravity. This theory challenges the sensory conflict perspective by proposing that motion sickness is linked to an inability to control posture

rather than just sensory mismatch. Furthermore, based on the fact that passengers are more prone to motion sickness than drivers [147], Wada *et al.* [174–177] offered a new explanation by proposing that the strategy for head tilting differs between drivers and passengers, influencing the incidence of motion sickness. The experiment demonstrated that passengers who tilt their heads toward the centripetal acceleration experience a significant reduction in motion sickness, regardless of the presence or absence of visual cues. When passengers engage in NDRTs, like reading a book or watching a movie, there is often an increased likelihood of experiencing motion sickness due to them tilting their head downwards (holding the display or book on their lap), with such a head position leading to increased motion sickness [31, 88] as well as due to them potentially occluding visual information from their surrounding, thereby creating a conflict between visual and vestibular-perceived self-motion.

However, research by Warwick *et al.* [180] did not support the Postural Instability Theory and instead provided evidence for the Sensory Conflict Theory. They originally believed that an inability to maintain a stable posture, due to disrupted postural sway and impaired understanding of one's centre of gravity, would lead to motion sickness. However, their study results were contrary to the expectations set by the Postural Instability Theory. Despite attempts to minimize postural control challenges, all participants still experienced motion sickness. These findings suggested that postural control alone might not be the critical factor in the onset of motion sickness, thereby questioning the theory's validity. More recent studies suggest a complex relationship rather than direct causation between postural instability and motion sickness. Stofregen *et al.* [160] consider postural instability could be considered a precursor or accompanying factor, rather than the primary source of motion sickness.

Sopite Syndrome [53], as described by Graybiel and Knepton is relevant to discussions of motion sickness. This syndrome is characterized by fatigue and mood changes related to both observed and perceived motion. However, Sopite Syndrome is considered a parallel phenomenon with motion sickness rather than a causal factor, as it arises from similar motion-related stimuli. The research by Warwick-Evans *et al.* underscores the importance of considering multiple factors in understanding motion sickness. It challenges researchers to look beyond single-cause explanations and to explore how various physiological and sensory processes interact. This nuanced understanding is essential for developing effective strategies to predict, prevent, and treat motion sickness in various contexts.

2.2.2 Relationship Between Motion Sickness, Simulator Sickness and Cybersickness

Based on different inducing contexts, motion sickness can be categorized into traditional motion sickness (triggered by real vehicle movements, e.g., cars, ships), simulator sickness, and cybersickness. Table 2.1 presents the characteristics of the three types of sickness.

	MS	SS	CS
Primary context	Real transport (car/ship/air)	Training simulators (screen with/without motion platform)	VR/AR; consumer interactive 3D
Dominant cue pattern	Vestibular: strong; Visual: weak/static	Visual: strong; Vestibular: still/weak	Visual: strong; Vestibular: still/weak
Typical triggers	Reading in a moving car; looking sideways in waves	Large-FOV optic flow; projection errors; display latency	Motion-to-photon latency; tracking error; unstable FPS;
Device-specific factors	Real vehicle dynamics	Screen alignment; motion-platform mismatch	Near-eye optics; reprojection artifacts

Table 2.1: Distinguishing motion sickness (MS), simulator sickness (SS), and cybersickness (CS).

Traditional motion sickness refers to symptoms such as dizziness and nausea occurring in real transportation settings (e.g., cars, ships, airplanes), primarily caused by sensory conflicts between vestibular inputs and visual/proprioceptive cues. The sensory conflict theory intuitively explains this phenomenon: mismatches among visual, vestibular, and proprioceptive inputs induce discomfort [145]. For instance, when traveling by car, the inner ear detects motion, but visual focus on a stationary interior object creates sensory conflict, causing motion sickness. The postural instability theory also applies, suggesting abnormal postural adjustments in unstable environments may trigger motion sickness symptoms.

Simulator sickness occurs within simulated environments, such as flight simulator training for pilots [95]. Typically, these environments involve minimal or no physical motion but visually present dynamic scenes while the body remains stationary, leading to sensory mismatches. Simulator sickness shares symptoms with traditional motion sickness, including discomfort, disorientation, fatigue, drowsiness, and nausea. It essentially represents a subtype of visually induced motion sickness (VIMS). The sensory conflict theory remains applicable here: visual perception of motion without corresponding vestibular/proprioceptive sensations generates sensory conflicts, inducing discomfort.

Cybersickness has emerged prominently with the widespread adoption of electronic displays and falls within VIMS, characterized by discomfort induced purely by visually simulated motion. In virtual environments, users perceive realistic three-dimensional dynamic scenes, creating illusions of self-motion while their bodies remain stationary. This condition leads to severe inconsistencies between visual inputs and vestibular/proprioceptive signals. For example, when playing computer games, players visually experience movement while physically stationary, generating similar sensory conflicts resulting in cybersickness. A typical instance in VR is visual latency: rapid head movements followed by delayed virtual viewpoint updates briefly induce sensory mismatches and instability, identified as a key factor triggering cybersickness. Cybersickness is purely visually induced without vestibular input, unlike traditional motion sick-

ness, which arises from vestibular motion coupled with conflicting visual cues (e.g., static car interior, non-driving-related tasks).

Given this study's emphasis on VR use in transportation, primary concerns regarding motion discomfort focus on traditional motion sickness and cybersickness. However, as VR displays—the primary inducers of cybersickness—are employed here specifically to provide visual cues aimed at mitigating motion sickness rather than causing VIMS, this study emphasizes mitigation strategies addressing traditional motion sickness rather than cybersickness.

In the context of transportation, where the use of new technologies is increasing, addressing motion sickness is crucial for enhancing user interaction within vehicles [156]. The introduction of these new technologies presents additional challenges; on one hand, the intersection of physical motion and virtual views can lead to an interplay between motion sickness and cybersickness, potentially exacerbating symptoms. On the other hand, well-designed virtual views can help alleviate motion sickness. The challenge lies in integrating these technologies into transport systems in a way that does not exacerbate—and might even improve—motion sickness symptoms. As VR is increasingly utilized for in-vehicle entertainment or operational purposes, understanding and mitigating motion sickness becomes critical.

2.2.3 Measures of Motion Sickness

Motion sickness is primarily evaluated through subjective self-report methods. These methods, including various rating scales and questionnaires, aim to capture the intensity and personal experience of symptoms [49, 79]. However, subjective measures alone have limitations, such as the lack of standardized instruments and reporting protocols. Consequently, there is a growing interest in identifying objective correlates that can supplement subjective assessments and enhance the accuracy and reliability of motion sickness measurement [8].

Subjective Measures

The most prevalent subjective measures for assessing motion sickness include questionnaires that evaluate an individual's susceptibility based on past experiences. The Motion Sickness Susceptibility Questionnaire (MSSQ) is frequently used, offering a historical perspective on an individual's experiences with motion sickness across various modes of transport [49]. An alternative is the Motion Sickness History Questionnaire (MHQ), which provides a more detailed exploration of individual symptoms and their frequency, though it is more time-consuming [55]. The Simulator Sickness Questionnaire (SSQ), developed by Kennedy *et al.* [78], is a widely used tool designed to assess symptoms specific to virtual simulator exposure. It comprises 16 items that participants rate based on their experience in a virtual environment, generating scores across three subscales: Nausea, Oculomotor, and Disorientation. Despite its origins in simulator research, the SSQ remains a standard in VR research. Table 2.2 presents the detailed sub-

components and assessment levels of the SSQ. As a post-assessment instrument, the Simulator Sickness Questionnaire (SSQ) provides a comprehensive evaluation of motion sickness symptoms. Being a subjective self-report measure, the SSQ is widely adopted in flight simulations, driving simulations, and contemporary VR studies due to its simplicity, ease of administration, and comprehensive coverage of typical symptoms. Although the SSQ remains one of the benchmark tools for assessing motion sickness, researchers are actively refining it to better align with current technological contexts. To cater specifically to the burgeoning VR research field, specialized scales have been developed. Notably, Kim et al. introduced the Virtual Reality Sickness Questionnaire (VRSQ) [82]. The VRSQ refines the SSQ by re-evaluating its symptom items through retesting and factor analysis, extracting nine symptoms most relevant to VR-induced motion sickness, thus forming a streamlined questionnaire. However, it is important to note that the VRSQ is still undergoing validation and wider dissemination. To address the need for real-time symptom tracking, the Fast Motion Sickness Scale (FMS) was developed by Keshavarz and Hecht [79]. This scale allows for continuous assessment of motion sickness symptoms, such as nausea and discomfort, on a minute-by-minute basis during VR exposure. The Fast Motion Sickness (FMS) scale provides a dynamic profile of symptom progression and can be effectively combined with post-exposure tools like the SSQ to offer detailed symptom insights. Another efficient and straightforward assessment tool is the Misery Scale (MISC), proposed by Bos *et al.* [12]. Characterized by its simplicity, the MISC consists of ten explicitly defined severity levels, making it particularly suitable for rapid assessments during VR tasks.

Despite the availability of these specialized scales, the SSQ remains the standard instrument utilized in most studies, owing to its extensive applicability and established validity.

Objective Measures

Researchers have investigated various physiological and neuronal correlates that could serve as objective indicators of motion sickness. Fundamental physiological measures such as heart rate [62], skin conductance [48], blink rate [103], and respiration rate [102] have been shown to correlate with motion sickness symptoms. These measures typically increase with symptom severity [29]. However, they are susceptible to confounding factors such as environmental conditions or other changes in the participants state such as fatigue, stress, arousal, which may limit their reliability. By analysing eye movement patterns and pupil data, researchers can infer levels of discomfort [127]. Eye tracking is advantageous due to its non-intrusive nature and ability to provide continuous data, making it a promising tool for the real-time assessment of motion sickness symptoms. Additionally, some objective measures that capture real-time changes in brain activity are gaining popularity [17]. Studies have investigated changes in electroencephalography (EEG) frequency bands, including delta, theta, and alpha, to identify neural correlates of motion sickness [70]. For instance, increases in delta power and changes in alpha activity have been associated with the stress and discomfort of motion sickness, though findings across studies

	None	Slight	Moderate	Severe
General discomfort	None	Slight	Moderate	Severe
Fatigue	None	Slight	Moderate	Severe
Headache	None	Slight	Moderate	Severe
Eye strain	None	Slight	Moderate	Severe
Difficulty focusing	None	Slight	Moderate	Severe
Increased salivation	None	Slight	Moderate	Severe
Sweating	None	Slight	Moderate	Severe
Nausea	None	Slight	Moderate	Severe
Difficulty concentrat- ing	None	Slight	Moderate	Severe
"Fullness of the head"	None	Slight	Moderate	Severe
Blurred vision	None	Slight	Moderate	Severe
Dizzy (eyes open)	None	Slight	Moderate	Severe
Dizzy (eyes closed)	None	Slight	Moderate	Severe
Vertigo (Giddiness)	None	Slight	Moderate	Severe
Stomach awareness	None	Slight	Moderate	Severe
Burping	None	Slight	Moderate	Severe

Table 2.2: Symptoms and Their Severity Levels in Simulator Sickness Questionnaire

vary, highlighting the complexity of neuronal responses to motion stimuli [168]. Other objective measures include postural stability assessments and neuroimaging techniques such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), which provide neurological insights into motion sickness, though their application is often limited by practical constraints such as cost and accessibility in routine research environments.

With technological advancements, new methods are emerging that overcome the limitations of traditional measurement tools. The integration of deep learning and facial recognition technologies enables the real-time prediction of motion sickness indicators. By analysing facial action units (AUs) and their dynamics, these systems can detect subtle physiological changes indicative of motion sickness, offering a non-invasive, continuous monitoring solution [97].

2.2.4 Individual Differences in the Experience of Motion Sickness

The variety of measures for assessing motion sickness, and the lack of a fully standardized approach, are largely due to individual differences in experiencing motion sickness. These differences are shaped by a complex interplay of factors, including field dependency, personality traits, age, gender, ethnicity, and prior exposure to motion-inducing environments. Field dependency, which refers to the reliance on visual versus vestibular cues, significantly influences the perception of self-motion. Research indicates that individuals who are highly field-dependent, relying more on visual cues, experience motion sickness more intensely and for longer durations compared to those who are less field-dependent [36]. Motion sickness susceptibility is

widespread, with reports indicating that as many as one in three people are highly susceptible [94]. While everyone is potentially susceptible, except those with complete labyrinth dysfunction [149], the severity and onset frequency of motion sickness symptoms vary significantly across different demographic groups. Gender differences are particularly notable, with females generally experiencing more severe symptoms than males. This heightened susceptibility in females is often attributed to hormonal influences, such as higher levels of estrogen, which are linked to increased motion sickness [106]. Additionally, differences in visual fixation patterns between genders may also contribute to this distinction, particularly in visually induced motion sickness scenarios [60].

Age is another critical factor. Among minors, susceptibility to motion sickness typically increases with age [170]. Among adults, the relationship between age and motion sickness is less clear, with some studies suggesting an increase in susceptibility with age [51], while others report a decrease [170]. This inconsistency highlights the importance of considering travel experience, as familiarity with different travel modalities can influence susceptibility independently of age [170]. Prior experience with motion-inducing environments, can also impact the severity of motion sickness. Behavioural adaptation may occur with repeated exposure to the same stimulus, such as frequent engagement with virtual environments, which can lead to less sickness in gamers compared to non-gamers in VR self-motion tasks due to sensory adaptation or habituation effects [140]. However, this adaptation is often considered temporary and specific to the type of stimulus, making it challenging to generalize across all types of motion sickness [157].

In addition to individual physiological and psychological factors, environmental conditions within transportation settings can significantly influence the onset and severity of motion sickness for some individuals [94]. For instance, studies have shown that strong or disagreeable odours, such as those from vehicle exhaust or food, can trigger or intensify nausea and other motion sickness symptoms. It is important to note that this impact varies among individuals. Some research highlights the lack of influence of pleasant or unpleasant odours on motion-induced sickness [125], while other studies suggest that olfaction can modulate motion sickness, with pleasant odours potentially reducing symptoms [80].

2.3 Future Passenger Experience

Individuals spend a considerable portion of their lives commuting in vehicles [165]. Recent estimates suggest that drivers collectively spend about one billion hours per day behind the wheel globally, with the average one-way commute in Great Britain is roughly 27–28 minutes [171]. Passengers engage in various non-driving activities inside vehicles, collectively referred to as Non-Driving Related Tasks (NDRTs). These activities are enabled by existing technologies, primarily relying on hardware such as in-car screens, tablets, and mobile phones. With the advancement of Automated Vehicles (AVs) and the consequent transition from drivers to pas-

sengers, individuals are likely to spend increased time in vehicles as passengers [54] as AVs promise to give back this time to passengers by freeing them from driving tasks. This prospect has profound implications for the in-car experience, as commuters could transform formerly idle driving hours into productive or enjoyable activities. With vehicle autonomy, occupants can engage in a variety of NDRTs during travel. Early research by Pfleging *et al.* surveyed potential activities in a driverless car, finding that passengers would do everything they typically do on public transport – such as making phone calls, browsing the web, and texting – and more once granted the privacy of a personal vehicle [99]. Envisioned uses include working on a laptop, reading books or papers, watching movies, playing games, catching up on news, or simply relaxing. These findings reinforce that occupants of future AVs will leverage travel time for both productivity and leisure. Researchers even forecast the advent of the “mobile home and office” – privately owned autonomous cars outfitted to be work and living spaces – which could vastly increase people’s ability to plan and utilize travel time for such NDRTs [99]. This underscores the necessity for more comfortable and ergonomic interaction methods for NDRTs in future AVs. Introducing AR/VR technologies could overcome these limitations and provide an immersive experience; however, the anticipated use of VR in vehicles brings with it certain challenges. This section will discuss the future development of autonomous vehicles and the VR-based passenger experiences of the future, along with the challenges posed by these technologies.

2.3.1 The Development and Future of Autonomous Vehicles

The idea of autonomous vehicles dates back to a century ago. In 1926, the radio-controlled car known as the “Linriccan Wonder” was regarded as one of the earliest instances of autonomous driving technology [9]. During the 1960s, multiple research facilities achieved autonomous high-speed driving on designated highways using embedded road detection signals, eliminating the need for human drivers [24, 164]. With the rapid advancements in vehicle energy sources and chip computing power, autonomous vehicles have experienced significant progress over the past two decades. In 2013, Tesla, a leader in electric vehicles, introduced its Autopilot system. Over the following decade, Autopilot underwent numerous hardware and software upgrades, evolving into the Full Self-Driving (FSD) version in 2020 [44]. By 2023, Tesla integrated end-to-end large models, bringing it closer to achieving full autonomy. In the same year, Mercedes-Benz demonstrated a S-Class car that autonomously drove 100 km on a German highway using radar and cameras. According to an IEEE forecast, by 2040, autonomous vehicles are expected to account for 75% of all vehicles [85].

The functionality of autonomous vehicles is categorized according to their level of automation. The most widely used classification system, established by the Society of Automotive Engineers (SAE) in 2016, defines six levels of automation, as shown in Table 2.3. At Level 0, the driver is responsible for all driving tasks. At Level 1, the autonomous system assists the driver with specific functions, such as highway cruising or emergency braking. At Level 2, the

SAE Level	Name	Execution of Steering and Acceleration/Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task
0	No Driving Automation	Human driver	Human driver	Human driver
1	Driver Assistance	Human driver and system	Human driver	Human driver
2	Partial Driving Automation	System	Human driver	Human driver
3	Conditional Driving Automation	System	System	Human driver
4	High Driving Automation	System	System	System
5	Full Automation	System	System	System

Table 2.3: Comparison of automation levels in vehicle technology based on SAE level

system handles tasks like acceleration and steering, but the driver must remain attentive and ready to intervene, avoiding distractions from non-driving-related tasks (NDRTs). At Level 3, the driver can largely transition to a passenger role in most scenarios, but must be prepared to intervene if an emergency arises. At Levels 4 and 5, the autonomous vehicle assumes full responsibility for all driving tasks, allowing the driver to completely disengage from the driving process.

Recent studies indicate that many vehicle manufacturers are moving towards Level 3 automation and actively exploring the design of SAE Level 4 and 5 autonomous vehicles [7]. The potential benefits of these higher levels of automation are substantial. In terms of safety, research suggests that autonomous vehicles are expected to significantly improve safety, as the majority of current accidents are caused by human error. Autonomous systems can reduce or eliminate driver fatigue, thus mitigating one of the primary causes of accidents [155]. Moreover, autonomous vehicles possess superior situational awareness, enabling them to better assess road conditions and respond more effectively in emergency situations. According to the survey [187], even at lower levels of automation, these technologies can enhance safety. Basic autonomous driving systems (below Level 3) have already reduced collisions by more than 30% annually [66]. Given the enhanced perception and decision-making capabilities of higher-level autonomous systems, this reduction rate is expected to significantly increase as the technology continues to develop.

The maturation of self-driving technology is fundamentally redefining the role of the person in the car. In traditional vehicles, the human is an active driver; with partial automation (SAE Level 2–3), the human becomes a system supervisor responsible for monitoring the automation; and at full automation (Level 4–5), the human is essentially a passenger – no longer required to

control the vehicle. This progression marks a shift from being a driver/operator to being a user of a mobility service. This shift elevates the importance of Non-Driving Related Tasks. As a result, passengers increasingly anticipate more innovative future passenger experiences.

2.3.2 Challenges and Design Opportunities in Future Passenger Experiences

Currently, phones, tablets, in-car screens, and laptops are common fixtures in vehicles, playing a crucial role for passengers by providing a variety of NDRTs. Existing NDRTs face numerous limitations. One significant constraint is the size and position of physical displays, which is limited by the spatial constraints of the vehicle interior [112]. Automotive comfort has traditionally focused on ergonomic factors such as seat shape, headrest positioning, and the isolation of static displays, all optimized for a forward-facing driver. However, these configurations are not ideal for mitigating motion sickness. Static displays, when misaligned with the passenger's movement, may exacerbate sensory conflicts [109]. Similarly, fixed seating positions and head postures designed for driving comfort inadvertently reinforce visual-vestibular mismatches [178]. This often forces passengers to turn/raise/lower their head to view the screen, which can encourage adverse effects such as motion sickness [126]. Such setups may increase the likelihood of motion sickness symptoms during NDRTs engagement.

Furthermore, individuals are often forced to make trade-off between maintaining the privacy and achieving optimal visibility angles in transportations [182]. Autonomous vehicles also herald new possibilities for social interaction inside the car – as well as new questions about privacy [182]. The balance between social and personal space also presents a nuanced design problem. As noted, an AV could be a convivial space or a private cocoon. Flexible interior architecture such as modular seats offers a solution, but implementing that flexibility is an open question. Future autonomous vehicles may introduce windowless setups and alternative seating arrangements, allowing for more flexible positioning of NDRT content, better aligning with ergonomic principles.

Also, the change from being a driver to a passenger sparked by autonomous vehicles, however, can lead to more experience of motion sickness. Passengers are generally more likely to experience motion sickness as they are less aware of the trajectory of the journey [67]. Therefore, the design of new NDRTs is essential. At the same time, as mentioned earlier, with the increasing prevalence and levels of automation in autonomous vehicles, the importance of NDRTs is also growing. This increase is driven by two main factors: the transformation of drivers into passengers, allowing more individuals to engage in NDRTs during travel, and an enhanced willingness to travel among passengers [92].

According to a study by Kyriakidis *et al.* [90], based on responses from 5,000 users, the higher the level of vehicle automation, the more likely respondents are to engage in secondary

tasks. The results showed a significant increase in the number of people who wanted to rest, sleep, watch movies, or read in fully autonomous driving mode. Real-world studies on Level 2 automated driving also reflect this trend, as highlighted by Morando *et al.* [117], where drivers exhibit fewer glances towards the road and a greater focus on NDRTs, such as engaging with mobile phones, compared to manual driving. Similar findings have been confirmed by insurance company. According to research by StateFarm [158], autonomous driving will free up time for both drivers and passengers, enabling them to engage in other activities. People are likely to read, browse the internet, and watch movies while in the car. The study also noted that as trust in autonomous driving technology grows, these tendencies are expected to increase further.

However, some studies present contrasting views. According to a survey by Lenz *et al.* [93], passengers in traditional vehicles still primarily focus on the ride and the route, with over 80% of participants reporting that they never engage in social networking activities, such as using a phone, emailing, or sending text messages, while driving. In contrast, when asked about their expectations for future autonomous vehicles, most participants believe that the way people use travel time will not undergo significant changes. This raises questions about the claims that autonomous driving will significantly improve or optimize the use of travel time. Such opinions highlight the importance of novel NDRTs and interaction modes, suggesting that users will require efficient and user-friendly NDRTs to shift their previous habits.

The concept of this new generation of NDRTs has received strong support from automotive manufacturers. Many companies have already showcased their visions for the content of NDRTs in future autonomous vehicles. For instance, Volvo's 360c concept eliminates the driver's seat, greatly enhancing the interior design space of the vehicle [172]. Such design also opens up the potential for windowless set-ups and different chair arrangements, which could contribute to more effective communication between passengers. At CES 2023, Audi presented its VR experience platform for passengers, which leverages vehicle digitalization technology to transform the interior into a third living space and lay the groundwork for future interactions within autonomous vehicles [4].

2.3.3 Virtual Reality in Future Passenger Experience

Benefits of Virtual Reality in Enhancing Passenger Experience

As the next-generation computing platform, Virtual Reality (VR) plays a crucial role in future passenger experience. Virtual reality refers to an immersive computer-generated experience that simulates presence in either real or imagined environments [173]. The core of VR lies in its ability to recreate a variety of sensory experiences, including sight, smell, and touch, although visual stimulation remains the most predominant [104]. This ability to simulate realistic environments has heightened public interest in VR technologies. The growing popularity of VR is largely attributed to its wide range of applications.

In the entertainment industry, VR offers users an enhanced and immersive experience, allowing them to explore virtual worlds with unprecedented realism and interactivity [154]. This has reshaped the way audiences consume digital content, with examples ranging from video games to virtual tours, establishing VR as an integral part of modern entertainment. Beyond entertainment, VR has found significant applications in the field of therapy. Researchers such as Fodor *et al.* [42] have demonstrated the potential of VR in therapeutic settings, utilizing virtual environments to treat various psychological disorders. VR therapy has been particularly effective in exposure therapy, where patients confront and manage their fears within a controlled, virtual space [43, 131]. This approach allows for a safe and flexible treatment environment, which can be customized to meet the specific needs of each patient. Furthermore, VR is increasingly being used in training and educational applications. Studies highlight the effectiveness of VR in simulating real-world scenarios for training purposes. VR training modules are employed across various sectors, including healthcare, aviation, and military, providing trainees with realistic practice environments without the associated risks and costs of traditional training methods [26, 74, 189]. The versatility and adaptability of VR technology continue to expand its applications across different domains, offering significant benefits and transforming how we interact with digital content. As VR technology continues to evolve, its potential impact on society is expected to grow, paving the way for new innovations and applications that further integrate virtual experiences into everyday life.

VR has demonstrated transformative capabilities in societal development, highlighting its immense potential to enhance the future passenger experience. The ability to create immersive environments that overcome the limitations of physical space is particularly relevant in the context of transportation, where two-dimensional (2D) physical constraints often limit the size and functionality of traditional displays [112]. Czerwinski *et al.* [25] suggest that larger and wider 2D display spaces can enhance productivity tasks, indicating a demand for more expansive visual environments. However, such demands are difficult to meet with conventional in-vehicle displays due to space restrictions [112]. VR headsets, on the other hand, circumvent these limitations by rendering content at any size, depth, or position around the passenger, thereby providing a versatile and expansive visual experience. Such 2D content remains a critical component of VR-based interactions. It encompasses a wide range of productivity and entertainment elements, such as web pages and videos [107].

Integrating VR into vehicles enables innovative ways to present NDRTs content on VR devices. This content can include streaming videos, such as television shows or movies, providing an immersive experience, and can also extend to increasing screen sizes or using multiple screens to display productivity-related content and workspaces [5, 6, 101, 107, 129]. Such designs can greatly enhance passenger entertainment and productivity [101]. By allowing users to simulate larger screens or multiple workspaces, VR headsets help overcome the limitations of mobile devices like smartphones and laptops. This capability not only improves the comfort

and ergonomics of the user experience but also creates new possibilities for human-computer interaction in transportation settings [107, 123].

As VR technology advances, it presents a promising solution to improve passenger experiences by alleviating the boredom and discomfort associated with long-distance travel [108]. The incorporation of VR technology in autonomous vehicles could lead to novel and stimulating experiences, expanding opportunities for entertainment and enhancing the overall travel experience. By harnessing the unique capabilities of VR, future transportation systems can create immersive and engaging environments tailored to the diverse needs of passengers, thereby redefining the concept of in-transit entertainment and productivity.

Challenges and Concerns in Implementing Virtual Reality

To realize the promising potential of VR technology in enhancing passenger experiences, it is essential to address the current challenges associated with its use, particularly those related to social acceptability, technical limitations, interaction in constrained spaces, and motion sickness [108].

There are barriers to the social acceptance and adoption of VR technology in public transportation environments. A significant issue is the reluctance to become fully immersed in a vehicle due to mistrust or safety concerns. VR headsets can obstruct a user's ability to quickly respond to real-world events, such as vehicle stops or emergencies, and ensuring physical crash safety is a critical consideration in worst-case scenarios [108]. Additionally, wearing a VR headset can isolate users from their immediate surroundings, potentially leading to discomfort or social awkwardness in shared public transport settings.

Technical limitations, such as display lag and low frame rates, can also contribute to cybersickness and detract from the user experience [71]. While advancements have significantly reduced these adverse symptoms, ongoing development is necessary to eliminate them completely [45]. Manufacturers are continuously working on improving these aspects, but until they are resolved, they will remain significant barriers to the widespread adoption of VR in transit.

Another critical area of concern is the integration of VR with existing transportation systems and infrastructure. Developing low-latency interfaces that can effectively interact with various vehicle systems is essential [111]. For example, VR systems must adapt to different vehicle dynamics and maintain synchronization with real-world motion to reduce motion sickness and enhance user experience. This integration challenge is further complicated by the need for compatibility across diverse transportation modes, including airplanes, trains, and buses.

The most significant impediment to the widespread adoption of VR in transit environments is the issue of motion sickness. Motion sickness is a primary concern when displaying content via VR, characterized by symptoms such as nausea, dizziness, cold sweats, and even vomiting [89]. These symptoms can be both immediate and prolonged, lasting several hours after onset and significantly impairing user comfort [32]. The most widely accepted explanation for

motion sickness is the sensory mismatch between the visual and vestibular systems [73, 145]. While travelling by vehicle, passengers encounter various motion sickness stimuli, and the prolonged commuting times anticipated for autonomous vehicles (AVs) further exacerbate these concerns [27, 54]. As noted by Isu *et al.*, a typical case of motion sickness in vehicles occurs when passengers use screen-based electronic devices [68]. This type of motion sickness intensifies when the visual information from fixed screens conflicts with sensory inputs from the vestibular system detecting passive self-motion, creating a dissonance that can lead to discomfort. Such discomfort can significantly compromise the passenger experience, undermining the potential for productive use of travel time [32]. This issue could be even more pronounced in VR, where users are fully immersed in a virtual environment and unable to see the outside world. Therefore, addressing the challenges posed by motion sickness is crucial for the future use of VR technology in transportation and is a key focus of this paper.

2.4 Motion Sickness Mitigations

Efforts to mitigate motion sickness have led to the development of various interventions, from behavioural strategies [146] and pharmacological treatments [84] to technological innovations [96, 109] aimed at reducing sensory conflict. Despite these advancements, motion sickness remains a significant challenge, particularly in situations involving new technologies like virtual reality environments.

Understanding the causes of motion sickness and anticipating future passenger experiences allows for the effective integration of these themes to explore improved strategies for alleviating motion sickness in future passenger settings. This chapter is divided into two main sections. The first section discusses how future vehicles may contribute to motion sickness and outlines potential mitigation strategies. The second section examines the contribution of passenger-centric motion sickness alleviation strategies to future passenger experiences. By combining these mitigation strategies, VR technology, with its unique advantages, is poised to play a significant role in enhancing future passenger experiences.

2.4.1 Motion Sickness Mitigations: Vehicle-Centric Design

The advent of autonomous vehicles AVs offers a transformative potential for future transportation. However, it also presents considerable challenges, particularly in addressing motion sickness. Unlike traditional vehicles, where drivers can anticipate movements and thus experience reduced motion sickness [147], passengers in AVs are more vulnerable due to their passive roles and inability to predict vehicle trajectories. To tackle this issue, researchers have proposed a range of car centric mitigation strategies for future AV designs. Unlike the passenger-centric mitigation strategies discussed later in this paper, traditional vehicle engineering primarily fo-

cuses on reducing motion stimuli, aiming to delay the onset of motion sickness by minimizing the intensity of such stimuli.

In conventional vehicles, passive suspension systems primarily focus on dampening vertical vibrations (1–2 Hz) to enhance ride comfort. However, these systems are ineffective against low-frequency motions (<0.5 Hz), which are a major contributor to motion sickness [35]. Active suspension systems in future AVs promise to significantly improve passenger comfort by effectively absorbing vertical motion caused by uneven road surfaces [34]. For instance, Zhao *et al.* [192] developed a PID algorithm that optimizes performance indicators such as body acceleration and suspension dynamic deflection. This optimization effectively reduces the incidence of motion sickness by minimizing ground roughness excitation and enhancing vehicle handling stability. The integration of such technologies in future AVs could greatly mitigate the impact of vertical vibrations on motion sickness.

Nevertheless, challenges persist in addressing other contributors to motion sickness, such as horizontal motion and rotation, which are intrinsic to vehicle dynamics and cannot be entirely eliminated. Comfort motion planning offers a viable solution to some of these concerns. This approach involves using specialized algorithms within AV control systems to generate smooth and comfortable motion trajectories [191]. The objective is to minimize abrupt movements, acceleration, and deceleration, ensuring a pleasant and comfortable experience for passengers [91]. Comfort motion planning considers various factors, including vehicle dynamics, road conditions, speed limits, traffic patterns, and passenger preferences. By optimizing trajectory planning, it reduces sudden speed changes, sharp turns, and abrupt stops, leading to a smoother ride, reduced motion sickness, and enhanced overall satisfaction [63]. Thus, a comprehensive approach that combines active suspension systems with comfort motion planning could provide a more effective mitigation strategy, paving the way for a smoother and more comfortable ride in future AVs. Also, improving passengers' situational awareness is crucial for reducing motion sickness. Technologies that provide real-time visual cues about anticipated trajectories can help align passengers' vestibular and visual inputs, thus alleviating motion sickness symptoms [11]. Additionally, innovative seat designs and orientations play a significant role in mitigating motion sickness. While face-to-face seating arrangements in AVs promote social interaction, they can hinder passengers' ability to anticipate vehicle movements [30]. Adjustable seats that allow passengers to face the direction of travel or provide support during vehicle maneuvers can improve comfort and reduce sensory conflicts [150].

As autonomous vehicles become more prevalent, addressing motion sickness through innovative technological solutions is essential. By leveraging advancements in vehicle dynamics and passenger comfort technologies, future AVs can provide a more comfortable and enjoyable passenger experience. These technologies represent critical directions for the development of AVs.

2.4.2 Motion Sickness Mitigations: Passenger-Centric Sensory Cues

In the area of vehicle design, technologies mentioned in the previous section have predominantly focused on decelerating the vehicle to reduce the motion experienced by passengers. In contrast, numerous studies have adopted a more passenger-centric approach by designing visual and multimodal motion cues that align with vehicle movements to alleviate motion sickness. Many of these cues are based on visual stimuli and are grounded in established motion sickness theories, generating various types of sensory inputs that contribute to effective mitigation strategies.

This chapter first provide a comprehensive review of previous research on the use of visual cues to reduce motion sickness in automated vehicles. According to Emond *et al.* [39], these visual cues can be categorized into four main types, as summarized in Table 2.4. The following sections will build upon this table to explore and expand each category in depth. In addition, some studies have experimented with multimodal cues, including auditory and haptic stimuli, to further reduce motion sickness. These efforts have added diversity and depth to research in this area.

Visual Design Categories
Displaying the vehicle's front view
Displaying artificial visual references synchronized with the vehicle's motion forces
Moving or rotating the entire visual content of the NDRT according to the vehicle's motion forces
Presenting anticipatory visual signals of the vehicle's future motion

Table 2.4: Visual Cues Design Categories Based on Classification [39]

Displaying artificial visual references synchronized with the vehicle's motion forces

Displaying the vehicle's front view and artificial visual references: *matched motion cues*

Returning to the widely accepted Sensory Conflict Theory [145], motion sickness arises from discrepancies among visual, vestibular, and proprioceptive sensory inputs. A key trigger of motion sickness during NDRTs is the absence of visual information reflecting the vehicle's motion and the external environment. Therefore, if the actual visual input is aligned with the bodily sensations—namely, the vehicle's movements—motion sickness can be effectively mitigated. These designs are widely known as *matched motion*. A straightforward strategy to address this is to provide visual cues that display the vehicle's front view, compensating for the blocked external view. Beyond the vehicle's front view, such cues can also take the form of artificial visual references that are synchronized with the vehicle's motion forces. Therefore, the first two categories in Table 2.4 are discussed together in this chapter under the theme of *matched motion*.

In the context of car transportation, having an external view has been shown to significantly influence the modulation of motion sickness [11]. Proper use of visual information can reduce the severity of motion sickness by up to 90% [116]. Consequently, visual cues, have been

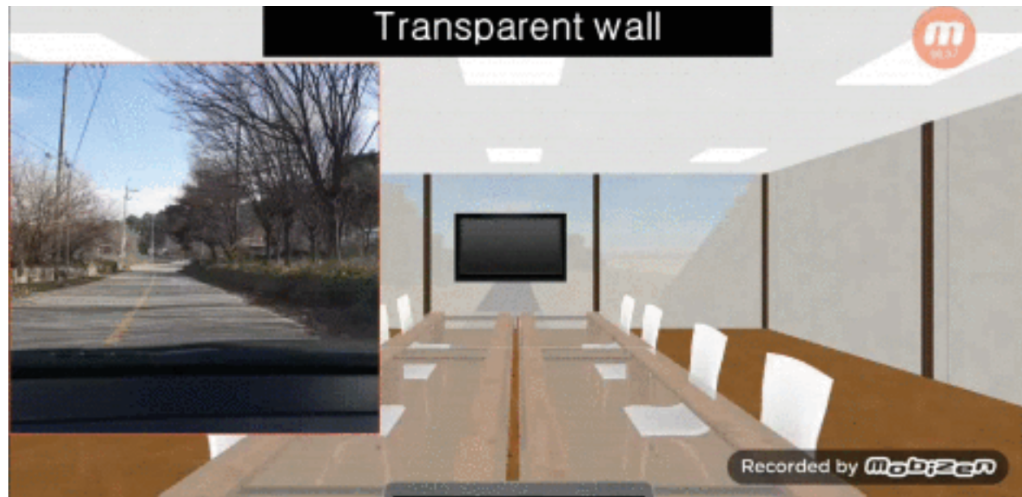


Figure 2.1: Transparent wall design: Visual motion is observed through the transparent wall in the background. Image adapted from [20].

recognized as a leading strategy for mitigating motion sickness in vehicles [88]. Miksch *et al.* [114] projected a real-time video stream of the driving environment onto the background of text while passengers were reading. This approach allowed passengers to maintain alignment between their vestibular and visual information, even while engaged in reading. The study demonstrated the potential of this approach by using a display to show images from a camera positioned behind the windshield, thus compensating for the blocked view.

Artificially designed visual references also represent significant attempts in providing matched visual cues. Cho and Kim's real-world study [19] compared a artificially virtual space cues, which converts the vehicle's motion forces into the movement of virtual space, with a design lacking additional visual cues. Their findings showed a reduction in motion sickness. Although the test duration for each group was relatively short, only five minutes, their study still provided valuable insights for future design directions in this area.

Many VR research studies have also concentrated on sensory conflict theory, developing visual cues designed to replicate the motion that passengers would typically perceive from the external environment [19, 76, 109, 122, 136, 138]. Suwa *et al.* [162] developed a similar design for viewing fixed 2D content on VR. In their study, participants performed reading tasks on a vibrating platform, comparing two background conditions: a white background, which did not allow for visual perception of movement, and a camera background, which provided movement perception through the front camera. The results indicated that motion sickness was significantly reduced in the camera background condition. Similarly, a real-world road test using a transparent wall in VR [20], which displayed the vehicle's motion forces on the background walls in VR. Figure 2.1 illustrates this design, where information from outside the vehicle is conveyed into the VR environment through semi-transparent walls. Their results showed a reduction in motion sickness.

By delivering self-motion information congruent with visual self-motion cues normally ex-

perienced during a car journey, these designs effectively reduce the sensory conflict between the visual and vestibular systems [19, 61, 110, 111]. These visual cues are often presented in the background, independent of a productivity or entertainment task. Visual cues can be integrated into the virtual experience in various ways, including through virtual/real scenes [19, 138] or starfields [81, 122, 128] that simulate external motion information.

However, although *matched motion* has been shown to be effective in many studies and holds promise as one of the most optimal mitigation strategies, some research has reported mixed or contradictory results. Karjanto *et al.* [75] designed a visual peripheral information system (VPIS) based on visual cues, which displayed information from the front of the vehicle's windshield on a 4-inch display. Real-world vehicle experiments revealed that this design actually exacerbated the experienced motion sickness. This might be due to the movement of the 4-inch screen and the reading task, which induced visually induced motion sickness, a condition distinct from typical motion sickness but with similar symptoms. Similarly, earlier studies by Griffin and Newman [56] indicated that provision of a real-time video view of the road ahead did not reduce motion sickness. Due to the early stage of their experiments and the limitations in screen hardware, the results may also have been influenced by the position and display quality of the screen. This indicates that more considerations are needed when designing visual cues.

Moving or rotating the entire visual content of the NDRT according to the vehicle's motion forces

Morimoto *et al.* indicated that adjusting the spatial position and shape of video content to mimic the motions of the vehicle effectively diminished symptoms of motion sickness [118]. They proposed two approaches to reduce motion sickness while watching videos in a vehicle: distorting or moving the video to reflect the vehicle's motion. Figure 2.2 illustrates these two design approaches. This research paved the way for further studies using the movement of NDRTs content itself as a visual cue. In a related study, Hanau and Popescu developed *MotionReader* [58], a technology incorporating analogous design principles. They examined the impact of different visual signals on e-readers, specifically through *Text Inertia*, which reflects acceleration data by shifting the virtual frame of the e-reader counter to the direction of acceleration. They suggested that further exploration of augmented reality might hold potential benefits. In their study, they also proposed an artificial visual reference known as the 'ball-spring' cue [58], which reflects the vehicle's motion forces through the stretching and compressing of a spring in response to the vehicle's movements. Participants were seated on a bus and viewed NDRTs content along with visual cues on a tablet screen. Despite their efforts, results indicated that this design actually worsened motion sickness symptoms, potentially due to the limited field of view.

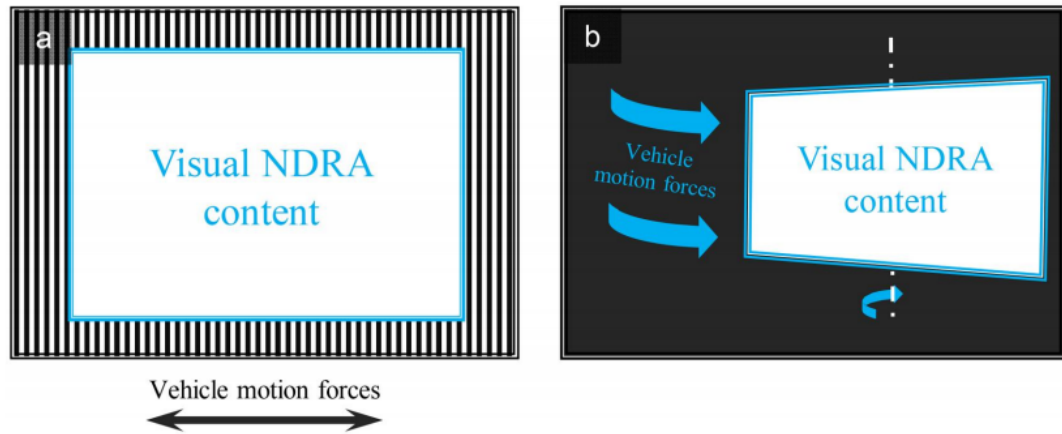


Figure 2.2: Two examples of visual cues involve moving or rotating the entire visual content. In these cases, the lateral movement or rotation of the entire NDRT interface is used as a visual cue. Adapted from [39].

Presenting anticipatory visual signals of the vehicle's future motion

Sawabe *et al.* [151] conducted an experiment where they induced a vector illusion called the Pseudo-acceleration stimulus. This stimulus triggered participants' anticipated responses to motion prior to actual acceleration. Figure 2.3 illustrates their design, where visual signals prepare passengers in advance for the vehicle's future motion. This approach was found to reduce the degree of conflict between visual and vestibular signals, thereby ameliorating symptoms of motion sickness. However, this type of design only validated the situation where the vehicle was moving uniformly. Nevertheless, their design demonstrated that even non-fully matched motion can aid in mitigating motion sickness. For common movements during vehicle motion, such as turning, additional countermeasures are required. Also, Karjanto *et al.* [76] investigated a Peripheral Visual Feedforward System (PVFS) in a prototype vehicle without a forward view, employing animated blue LED arrows visible in peripheral vision. These anticipatory signals, activated three seconds before turning maneuvers, significantly reduced the motion sickness scores by 75%. However, in subsequent experiments, when the PVFS was expanded to a Visual Peripheral Information System (VPIS), which combined real-time and predictive motion cues, it actually exacerbated motion sickness [75]. This adverse effect might be attributed to the overwhelming dynamic visual content and associated oculomotor issues. The contrast in results between studies could also relate to the type of NDRTs, as reading is more provocative than video-watching. These findings underscore the complexity of integrating visual cueing strategies in vehicles to effectively counteract motion sickness.

In the realm of automated vehicles, the challenge of mitigating motion sickness through anticipatory visual signals has gained significant attention. Brietzke *et al.* [13] explored a dual-section screen interface placed inside a vehicle, allocating 80% of the screen to NDRTs and 20% to vehicle motion information. They conducted a real-world vehicle experiment on motion

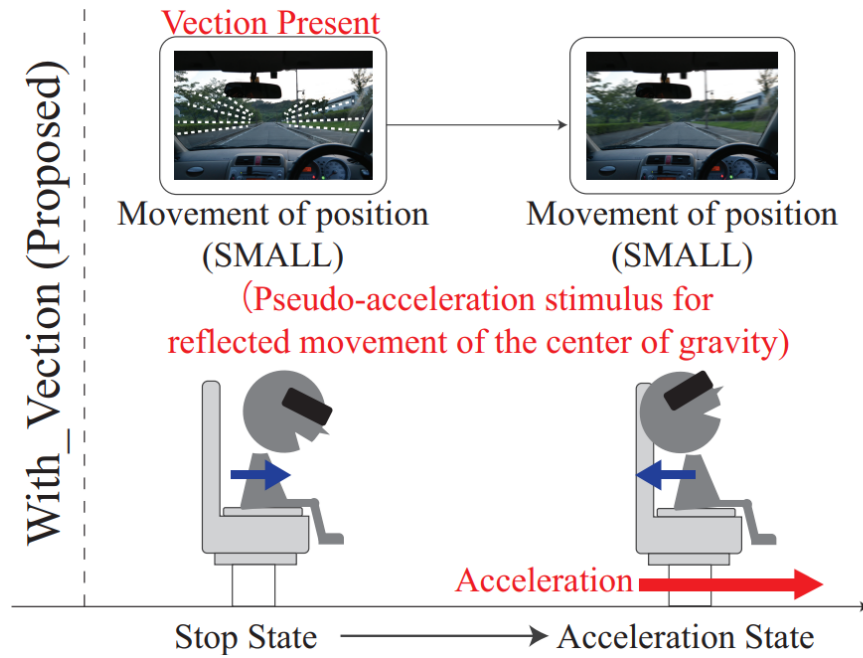


Figure 2.3: Pseudo-acceleration stimulus for reflected movement against the curved acceleration from the front view. Image adapted from [151].

sickness, asking participants to verbally rate three symptoms of motion sickness on a scale from zero to ten at one-minute intervals. While the results showed that participants did not experience relief from motion sickness symptoms, this outcome might have been influenced by factors such as the short exposure duration and screen positioning.

Multisensory Approaches

In addition to visual-based strategies, recent research has explored multimodal approaches for mitigating motion sickness. Auditory inputs have been proposed to support spatial orientation and reduce disorientation. One study using a rotating-chair VR setup found that adding spatialized motion-correlated sounds yielded modest symptom reduction (though visual signal alignment remained more effective overall) [185]. Weech *et al.* [181] also reviewed studies indicating that spatialized auditory motion cues may enhance presence and reduce cybersickness by improving the user's sense of motion congruence, although direct evidence on sickness reduction remains limited. In contrast, haptic feedback often shows stronger benefits. For example, an experiment with 80 users in a VR driving simulator demonstrated that providing synchronized engine vibrations alongside engine noise led to significantly lower sickness scores than either sound-only or vibration-only conditions [152]. Similarly, wearable haptic devices targeting the vestibular system have proven promising. Galvanic vestibular stimulation (GVS), which feeds low-current electrical signals to the inner ear in tune with virtual motion, has been shown to significantly cut down cybersickness discomfort by realigning vestibular perception with VR visuals [57]. Another novel approach delivers proprioceptive cues via muscle actuation: the

SYNC-VR system synchronizes an actual vehicle's movements with the VR experience and uses electrical muscle stimulation on the passenger's body to impart coordinated motion feedback, an in-car VR technique reported to reduce motion sickness and enhance user presence during autonomous transit [38]. Olfactory cues have been comparatively less studied but explored, pleasant odors would ease sickness and showed clear improvement over baseline [57].

In summary, these multimodal approaches from audio/haptic feedback and vestibular stimulation to ambient scent and body, underscore a growing toolkit for combating motion sickness in vehicle VR. They often yield partial relief but not a complete cure.

Semi-Matched Motion Cues: A New Design Direction

Extensive experiments and literature have demonstrated the importance of matched motion in alleviating motion sickness for passengers. This approach has gained a central role in mitigation strategies and is gradually becoming the gold standard. However, *matched motion* also faces several practical limitations.

Matched motion cues are typically driven by the motion platform's velocity, rotation angle, and pitch, and are presented in a 1:1 ratio to reflect actual vehicle movements. This approach is rooted in the sensory conflict theory. However, such strict coupling can make VR design inflexible, as cue generation is constrained by the vehicle's real-time dynamics, potentially limiting the experience. Moreover, this match may introduce distractions within the user's field of view.

A growing body of research has focused on the integration of non-1:1 matched motion cues into existing NRDTs content. Some studies have explored the interplay between visual display and motion sickness by investigating the effects of various non-matched starfield motion patterns [33, 40]. Sewon *et al.* has attempted to categorize actual motion information into linear and circular optical flow patterns, integrating these through the movement of a starfield in the VR content background, rather than directly conveying actual motion cues. These cue designs have not yet been implemented in VR/spatial computing, nor have they been systematically compared in effectiveness to the current gold standard of *matched motion* conveyances. This absence of controlled comparisons restricts our understanding from a vision science perspective.

Furthermore, while real-world studies involving actual vehicle motion [81, 122, 139] are considered the gold standard due to their higher ecological validity relative to studies that employ simulators [23, 138], the transmission of real-time, low-latency vehicle data to VR systems presents a significant challenge [111]. Some studies have utilized Inertial Measurement Units (IMUs) and On-Board Diagnostic (OBD) systems to obtain vehicle motion data like velocity and create VR content that matches the vehicle's physical motion [47, 61, 111, 122, 139]. These hardware solutions effectively support the data requirements for *matched motion*, but they pose significant challenges in terms of deployment compatibility and cost. Some designs are shifting towards using the device's built-in IMU and GNSS systems in combination to calculate vehicle motion [19, 20], thereby avoiding the need for additional components. However, according to

tests by McGill *et al.*, when retrieving velocity or velocity-related positional data, these methods may be prone to latency or drift issues [111]. These studies highlight the importance of effectively delivering motion cues based solely on VR devices. According to Meschtscherjakov *et al.*, a visual cue called *Bubble Margin*, which was only controlled by acceleration (obtained through electronic devices such as IMU), was shown to alleviate motion sickness during reading activities on mobile devices and can be integrated into various applications as an overlay [113]. With this integrated design, people can bring VR headsets onto any form of transport—buses, cars, and trains—instead of relying solely on specially equipped vehicles.

2.5 Distraction and Its Measurement

While *matched motion* can mitigate motion sickness, they may also detract from the overall user experience by diverting attention and causing distraction from the media content or NDRTs the passenger is attempting to engage in [109, 136, 188]. This section provides a review of how distraction is defined and measured in existing studies.

2.5.1 Definition of Distraction

In psychology, attention and distraction are closely intertwined, and understanding the latter requires first defining the former. Attention is defined as a set of cognitive mechanisms that select and filter stimuli and information processing to provide an appropriate response to primary tasks [22], while distraction is typically defined as factors that interfere with an individual's ability to complete a primary task. Based on this foundation, distraction can be categorized into three types [163]: multitasking interference, which occurs when a secondary task is performed alongside the main task, often weakening performance due to structural interference (e.g., using the same sensory or cognitive channels) or resource interference (limited attentional resources); external stimulus interference, which refers to visual, auditory, or motion stimuli unrelated to the task, but affecting performance due to overlapping sensory pathways or cognitive load; and mind-wandering, an internal thought process unrelated to the current task or environment, often observed in situations with minimal task load.

In VR visual cue distraction research, most studies use single-task settings and immerse participants in the scene to minimize multitasking and mind-wandering, focusing on the impact of visual stimuli on cognitive performance. In this setup, participants' sensory input is limited to the visual elements within the virtual interface, meaning that any non-task-related visual stimulus can lead to significant distraction.

2.5.2 Measuring Distraction: No Unified Standard

Evaluating distraction is critical for appropriately balancing motion sickness relief and distraction in VR. One of the main challenges in investigating distraction is the lack of direct measurement methods for the constructs [148], resulting in no unified measure to assess the degree of distraction [148].

Researchers measure distraction using a variety of objective and subjective approaches. One common objective measurement method is eye-tracking, which captures where and for how long users look at different objects. In automotive human–factors research, eye-tracking is considered the gold standard for detecting visual distraction [185]. For example, studies of augmented reality head-up displays (AR-HUDs) for drivers define specific Areas of Interest—such as the road ahead, pedestrians, or the HUD itself—and measure gaze metrics like fixation duration and frequency. In eye-tracking data, the number of times the gaze deviates from the Areas of Interest can indicate that a poorly designed display might draw attention away from the road too much [18]. Similarly, in VR settings, the entire visual field is virtual, but researchers can still track gaze within the headset. If users’ gaze frequently deviates toward added cues and away from relevant content, this suggests attentional distraction [161]. Ma *et al.* [105] found that when a passenger’s video screen was active, drivers showed longer average glance durations and fixations, reflecting an increased visual workload. Given the increasing affordability and integration of eye-tracking technology in many newer VR headsets, VR eye-tracking measures offer substantial application potential. Combining objective performance metrics with subjective assessments ensures robust detection of even subtle distractions induced by visual cues. Additionally, task setups in research can also contribute. These tasks range from mathematics-based exercises [141], reading [138], and video viewing [142], to more complex interactions.

Task accuracy and reaction time serve as metrics for assessing user attention. Although widely used, this approach can be influenced by participants’ educational backgrounds and prior knowledge. For example, a mathematician or aviation enthusiast might effortlessly complete relevant tasks, independent of attentional distraction. Coupling such gaze data with performance metrics provides an objective sense of distraction—if a participant’s gaze often wanders to a cue and their task performance drops, one can infer that the cue is too distracting.

In parallel with objective measurements, researchers also use subjective methods to capture the user’s perception of distraction. Such feedback is crucial in VR-in-vehicle studies to understand the felt experience of distraction. The simplest approach is to directly ask participants to rate how distracted or mentally taxed they felt. This can be done on a Likert scale (e.g., 1 = not at all distracted, 7 = extremely distracted, from [148]) or a more structured evaluation. When multiple conditions or interfaces are tested, researchers sometimes ask users to rank them by distraction level (e.g., *Distraction level rankings across all conditions* from [143]). Such single-item ratings are quick to administer and allow users to integrate all facets of distraction as they experienced it. Subjective impressions are valuable as they capture the human perspective on

distraction, which can guide design.

In summary, the evaluation of in-vehicle VR distraction balances both objective and subjective measures, with no unified and gold standard available. Objective metrics provide quantifiable evidence, while subjective ratings and questionnaires reveal the user's comfort and perception. Some studies often combine the two [148] to better understand the importance of distraction in design.

Chapter 3

Exploration of Visual Cues for Rotational Motion: Implicit Cues

3.1 Introduction

According to sensory conflict theory [144], motion sickness arises from a discrepancy between expected and actual sensory inputs from the vestibular and visual systems. In moving vehicles, passengers' vestibular systems perceive the vehicle's actual motion, while their visual systems receive conflicting cues from static interiors or onboard displays. VR headsets have the potential to mitigate motion sickness by providing synchronized visual information about external movements, thus reducing sensory mismatches [144, 190]. Numerous studies demonstrate that introducing supplementary visual motion cues effectively alleviates motion sickness [19, 20, 76, 88, 109, 134, 135]. Nevertheless, these additional cues may negatively impact user experience by diverting attention away from primary media content or NDRTs [109, 136, 188]. Psychological literature defines distraction as factors that disrupt an individual's ability to focus on a primary task [148].

Within VR environments, visual cues designed to mitigate motion sickness may conflict with the virtual context or NDRT content, compelling users to alternate attention between the cues and their intended tasks, thereby disrupting overall immersion. Additionally, visual cues typically placed around NDRT content exploit peripheral vision, which is highly sensitive to motion [109]. Consequently, any peripheral visual movement can involuntarily capture users' attention, detracting from their primary activity.

While the presence of visual cues may undermine VR immersion, their absence significantly increases motion sickness, negatively affecting users' enjoyment and potentially leading to rejection of VR technology. This dilemma underscores the necessity for developing motion cue designs that integrate seamlessly with the virtual environment, minimizing distraction and maintaining immersive quality while effectively reducing motion sickness.

As an initial step in exploring *minimally-disruptive motion cues*, the research focuses on ro-

tational motion—one of the most common and motion sickness-inducing movement experience in vehicles [115]. This chapter studies the implicit conveying of motion information through foreground movement—transmitting motion information implicitly and indirectly to achieve low distraction. This chapter includes two studies based on rotating planar 2D virtual displays. Such 2D displays are common in VR environments, as seen in Figure 3.1. They would occupy the majority of the available visual field in the headset, posing problems for the delivery of existing motion cues. The novel approach in this chapter subtly manipulates the virtual planar display (hereafter referred to as display) itself to convey information about motion implicitly interleaved with the VR content. The display design provides a visual cue of the experienced rotational motion of the passenger through changes in its yaw orientation relative to the user based on vehicle orientation changes.

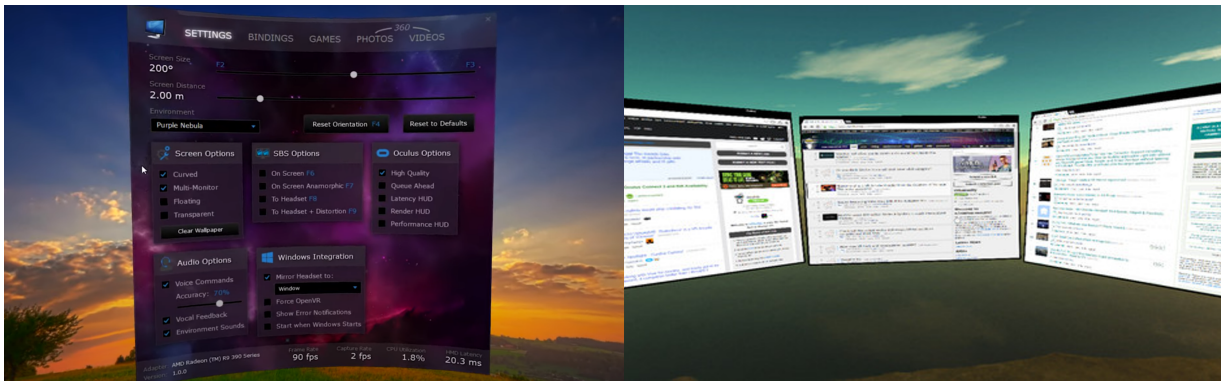


Figure 3.1: Examples of 2D virtual displays in VR. From left: Virtual Desktop [46], Multi-screens [132]

The studies explore whether the rotation of the display around the user in VR is an effective visual cue and could slow the onset of motion sickness. Study 1 examines the performance of two levels of rotational ratios (0.3 and 0.6) applied to the display and their effects on motion sickness. This experiment highlighted the beneficial effects of the smaller ratio of 0.3 on motion sickness. Informed by the results of Study 1, the design of Study 2 was refined to re-evaluate the 0.3 ratio. The study employed a multi-session format with prolonged condition exposure to enhance motion sickness induction, while sessions were scheduled on separate days to avoid cumulative symptoms. This chapter primarily addresses **RQ1.1** in **RQ1**:

- **RQ1**: For rotational motion, how is the trade-off between motion sickness and distraction impacted by visual cues that resolve sensory mismatch?
 - **RQ1.1** What are the effects of using implicit cues that manipulate the movements of 2D planar virtual interfaces?

3.2 Study 1: Preliminary Exploration of the Effectiveness of Rotating Display Cues

In this study, a new approach is developed to implicitly convey rotational motion cues by manipulating the orientation of presented 2D planar display (*hereafter referred to as display*) in real-time based on experienced external (physical) motion, as rendered using a VR headset. The design's performance in mitigating motion sickness induced by y-yaw rotation is explored at two levels of rotational ratios (0.3 and 0.6), testing the feasibility of the design.

3.2.1 Study Setup

Study 1 consisted of three conditions: Control Condition, the coefficient was set to 0, meaning that the task display was rotated to the same degree as the chair; and two experimental conditions: Condition 0.3 and Condition 0.6, described above. The display was rotated at a reduced angle based on the conditions compared to the degree of the chair rotation. For example, if the chair rotated 45 degrees in the 0.3 condition, the 2D display would rotate 31.5 degrees ($45 - 45 \times 0.3$). These coefficients, 0.3 and 0.6, were chosen to systematically vary the degree of decoupling between the chair's rotation and the task display, allowing us to study how different levels of rotation impact user perception and motion sickness. By adjusting the display's rotation in this manner, we aimed to understand the balance between maintaining immersion and reducing sensory conflict. The experiment employed a *within-subjects* design and all the conditions were administered on the same day. The order of the three conditions was counterbalanced according to a Latin square [130] to minimize order effects. Rotational motion is typically created using simulators or rotational chairs [138, 179]. These devices induce motion sickness through controlled and sustained rotational movements to test mitigation measures. Accordingly, this study utilizes a similar rotational chair to simulate vehicular motion and induce motion sickness.

3.2.2 Study Platform

A rotating chair (*RotoVR*) that can perform 1 Degree of Freedom rotations around the yaw-axis was used as a way to induce motion sickness, see Figure 3.2 left. This platform has already been proven in other studies to effectively induce motion sickness [134]. The rotations were scripted using a random function generator to rotate the chair at random intervals of 30, 45, or 90 degrees to the left or right. These angles were proposed by Feng *et al.* as the idealized base for the structure of urban road networks [16]. In order to achieve a uniform distribution of rotational angles, we additionally included 60 degrees as a transitional value between 45 and 90 degrees. The interval between each rotation was approximately 5 seconds. The *Meta Quest 2* was used as the VR platform. Throughout the study, participants were wearing the VR

headset while seated on the rotating chair, see Figure 3.2 right. This experiment was approved by the University Ethics Committee. For Study 1, there were a total of 3 conditions, with each condition set to 5 minutes to accumulate motion sickness.



Figure 3.2: On the left is the *RotoVR* rotating chair. On the right is a participant undergoing rotational motions on the chair.

3.2.3 Measurement Method

Motion Sickness Measurement

Two methods for measuring motion sickness were used. The first was the Simulation Sickness Questionnaire (SSQ, [78]). After completing a condition of the experiment, the participants filled in the SSQ describing their experiences and the level of motion sickness they felt during the condition. The second method was a 7-point real-time motion sickness rating slider, see Table 3.1. The slider was from [56] and was displayed at the bottom of the VR screen throughout the experiment. Participants could continuously rate their motion sickness using the slider. The maximum value and average value of this slider is utilized to reflect the participant's level of discomfort experienced during the experiment. To ensure that participants did not forget about the slider during the experiment, a reminder prompt appeared above it approximately every 30 seconds, encouraging them to indicate their level of motion sickness by adjusting the slider's

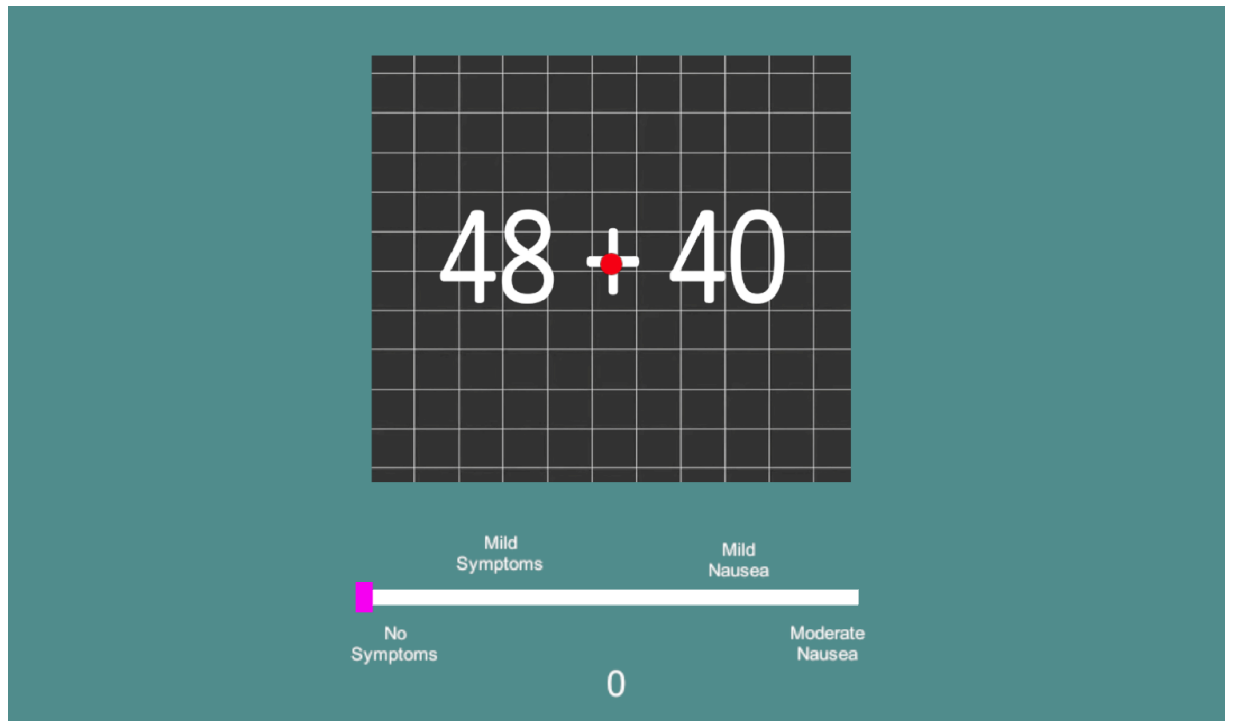


Figure 3.3: A screenshot is shown, which mirrors the participant’s visual display. The display presents a maths question, a red dot for the attention task, and a slider to allow the participant to indicate their real-time level of motion sickness.

value. If a participant’s rating reached a value of 7 (moderate nausea, according to the scale labels), the experiment was terminated to ensure the participant’s safety. Before participating in the experiment, participants were informed about this threshold.

The Motion Sickness Susceptibility Questionnaire (MSSQ) [50], was utilized to screen participants. This questionnaire is divided into two sections, each querying past occurrences of motion sickness during travel in vehicles such as cars, buses, coaches, and trains, as well as on small boats, ships, playground swings, and theme park rides. The first section focuses on the individual’s history of motion sickness before the age of 12, whereas the second section addresses incidents that occurred within the last ten years. To ensure participant safety, individuals with a history of severe motion sickness (Motion Sickness Susceptibility Questionnaire total scores over 30 [49]) were excluded from the study.

Productivity Measurement

A maths task involving two-digit addition and subtraction was used for the primary task, simulating a productivity activity, see Figure 3.3. Similar maths tasks have been widely used in previous studies as an assessment of participants’ cognitive ability and workload capacity [21, 37]. Participants were instructed to provide the answer verbally for each question as quickly as possible. The questions were updated every seven seconds, and providing no answer was counted as a wrong answer. The task was chosen because it is fair to all participants regardless of their

Table 3.1: Motion sickness slider measurement and description.

Value	Description
0	No symptoms
1	Any symptoms
2	Mild symptoms
3	Medium symptoms
4	Slight nausea
5	Mild nausea
6	Mild to moderate nausea
7	Moderate nausea (experiment stop line)

language backgrounds, avoiding the disadvantage of non-native speakers with slower reading speeds in tasks involving text [133]. Additionally, a secondary attention task was implemented that required participants to press the trigger on the VR controller when the red dot in the middle of the screen turned blue. This task was designed to ensure that participants maintained visual attention on the task at hand, based on work by Kooijman and colleagues [86]. It was important to keep their attention focused on the task to prevent data distortion caused by participants becoming completely distracted during the task. Furthermore, maintaining attention ensured that the visual cues remained effective, as the task was positioned at the center of the 2D display, and the display's rotation movement itself constituted part of the visual cues.

3.2.4 Visual Cues Design

In the VR display, the maths problem, motion sickness slider, and secondary attention task were all presented in the same 2D plane as shown in Figure 3.3. As the content of the VR background, such as the virtual horizon [59], can influence motion sickness, the background was set to a solid colour to avoid effects of background on motion sickness and distraction. The black background of the task plane was enhanced with white grid lines to distinguish it from the plain spatial background and to make the interface more visually prominent.

The rotation of the 2D display around the participant was used as a visual cue to alleviate motion sickness. Taking a 90° rotation of the chair to the right as an example, the participant's field of view would rotate 90° to the right, following both the physical rotation of the chair and the VR scene. However, if the 2D plane remained stationary (anchored at a distant location in physical space rather than moving with the VR viewpoint), the participant would perceive the plane as gradually rotating 90° to the left due to relative motion. In reality, this apparent rotation arises from the participant's field of view rotating to the right. This would serve as a clear visual cue to match the vestibular motion. However, this rotation would make the 2D plane very difficult to see because its position would exceed the VR device's field of view [65]. When the 2D plane was matched to the chair rotation and no visual rotation was applied, it would be

easy to see as the plane would remain in front of the chair, but there would be a strong mismatch between visual and vestibular perception, leading to motion sickness. The hypothesis was that a smaller rotation of the 2D plane in the same direction as chair rotation would be enough to provide a visual cue that partially matched the vestibular perceived rotation, and thus reduce motion sickness without affecting the view of the plane. When the chair rotation stopped, the position of the task plane was reset to be directly in front of the participant's field of view to ensure that the participant's head faces forward.

When applying the visual motion sickness mitigation cues, the task plane rotated in the same direction as the chair's movement but to a lesser degree. We used chair rotation angle – (chair rotation angle $\times$ coefficient X) to control the task plane's rotated degree. Increasing the value of X results in a smaller rotation angle. Figure 3.4 illustrates the movement of the task plane when X is set to 0.3 and 0.6 for a 90° chair rotation. The value of 0.6 was chosen as it enabled participants to view the entire maths task without having to turn their heads in VR, even when the chair was rotated to its maximum 90° angle.

The reason for setting this coefficient is that multiple studies have already proven that active or passive head movements can exacerbate motion sickness [100,119,178]. The value of 0.3 was selected as a compromise between 0.6 and no display visual cues (coefficient 0). This reduction to 0.3 would increase the rotation angle. This was made to investigate whether larger rotation angles (display rotation angle is closer to the chair's actual angle) could provide enough motion information.

3.2.5 Study Procedure

First, participants undertook training that was used to help those who were unfamiliar with VR and lasted for two minutes. They performed maths tasks identical in format to the experimental tasks and in the same virtual environment as the main experiment. The training was designed to ensure participant familiarity with the VR environment and experimental procedures before starting the experiment. As the training did not involve any chair rotation and lasted for a short duration, it did not induce any motion or simulator sickness. After completing the training, participants were given a few minutes of rest until they felt ready to continue.

Once the training was completed, participants performed the three different conditions, each condition lasted five minutes and participants performed the maths task while being rotated on the chair and rating their sickness level using the motion sickness slider. Before each condition, participants were required to answer the SSQ questionnaire to ensure the absence of motion sickness-related symptoms and minimise carry over effects from one condition to another. After each condition, participants again answered the SSQ questionnaire to measure their symptoms after exposure. Between each condition, participants rested for ten minutes to reduce the cumulative effects of motion sickness. The next condition would start only when they were certain that they did not exhibit any symptoms listed on the SSQ.

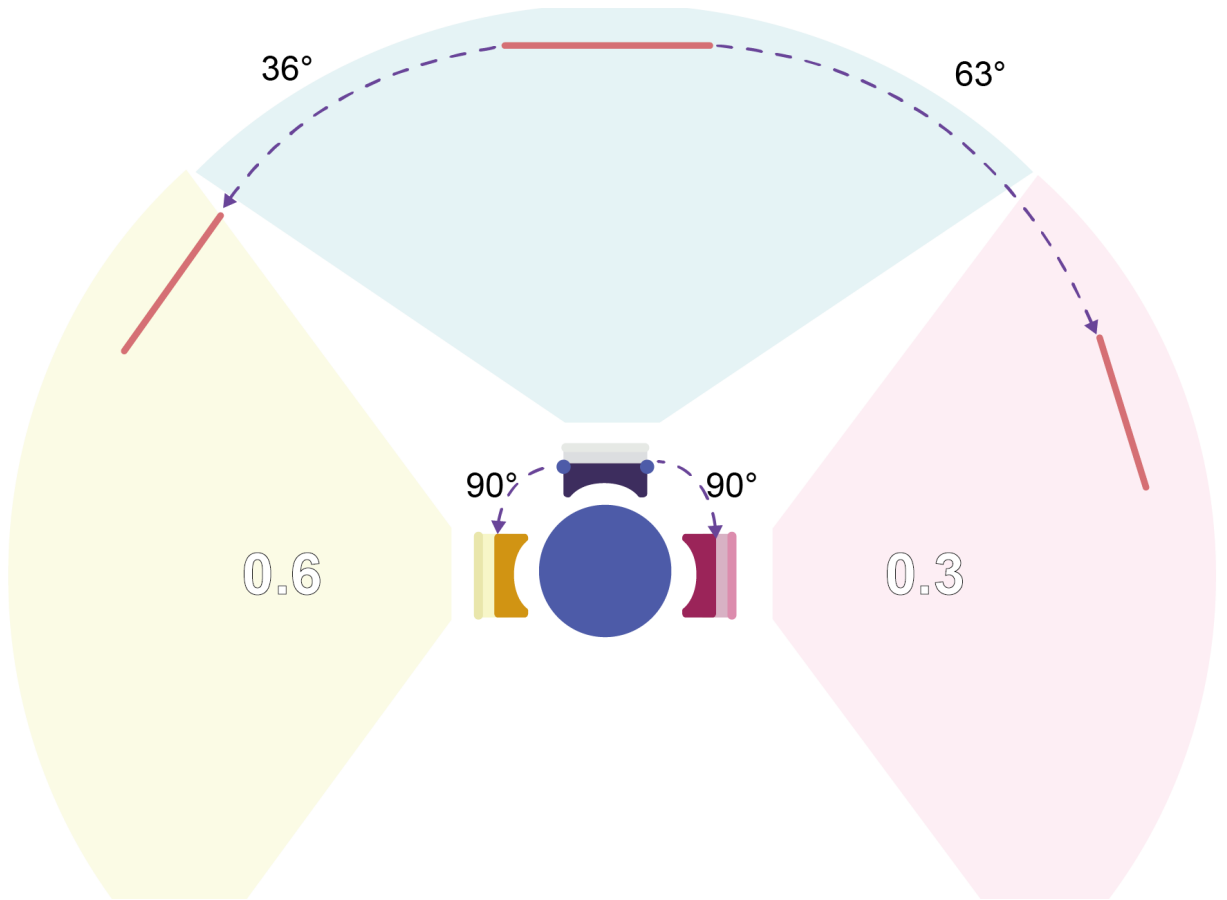


Figure 3.4: A top-down view of the visual cue movement. The shaded areas represents the VR field of view, and the red line depicts the top-down view of the 2D task plane. The user is at the centre, sat on the *RotoVR* rotating chair. In the case shown on the right, the coefficient X was set to 0.3, with both the participant and *RotoVR* rotated 90° to the right. As a result, the red task plane was rotated 63° ($90 - 90 \times 0.3$) to the right. In the case shown on the left, the coefficient X was set to 0.6, so the task plane was only rotated 36° ($90 - 90 \times 0.6$).

3.2.6 Results

The design resulted in a motion sickness across all conditions. Since the data did not meet the assumption of normality, a Friedman's ANOVA was employed for non-parametric statistical analysis, followed by pairwise comparisons with Bonferroni correction for *post hoc* comparisons among the different experimental conditions.

Motion sickness slider maximum scores

The maximum value of the Motion Sickness slider during each 5-minute route was calculated. No significant differences were found between conditions (Control condition ($M = 1.10, SD = 1.20$), Condition 0.3 ($M = .80, SD = .75$), and Condition 0.6 ($M = 1.20, SD = 1.26$), $\chi^2(2) = 4.33, p = .115$).

Motion sickness slider average scores

The average value of the Motion Sickness slider during each 5-minute route was calculated. No significant differences were found between conditions (Control condition ($M = .43$, $SD = .59$), Condition 0.3 ($M = .33$, $SD = .40$), and Condition 0.6 ($M = .50$, $SD = .51$), $\chi^2(2) = 4.46$, $p = .108$).

SSQ Nausea Subscale

The Nausea subscale of the SSQ was analysed separately because it is the subscale most strongly associated with symptoms of motion sickness. Nausea ratings differed significantly between the conditions, $\chi^2(2) = 12.23$, $p = .003$, Cohen's $F^2 = .02$. *Post hoc* tests revealed a significant difference between the Control condition ($M = 24.07$, $SD = 20.15$) and Condition 0.3 ($M = 10.44$, $SD = 11.64$, $p = .010$). No significant differences were found between the Control condition and Condition 0.6 ($M = 20.44$, $SD = 1.82$, $p = .948$), nor between Condition 0.3 and Condition 0.6 ($p = .161$), see Figure 3.5.

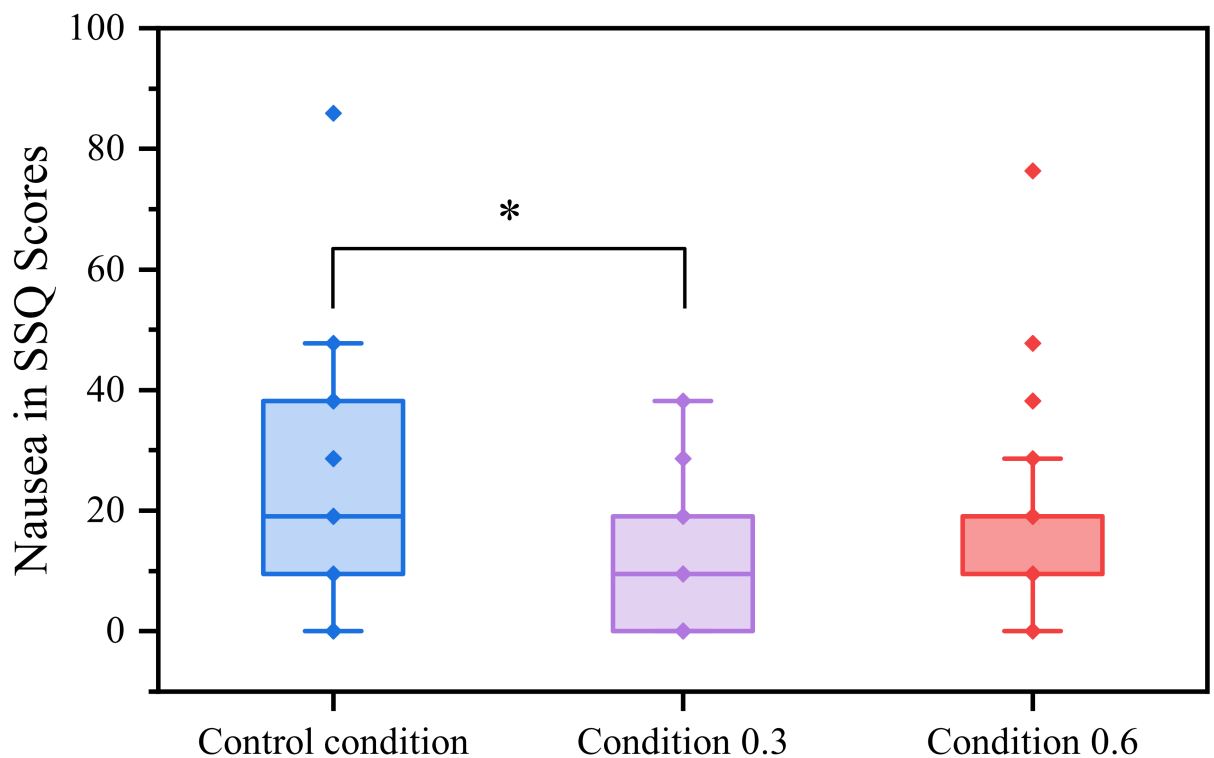


Figure 3.5: The Nausea related symptoms subscale from the SSQ. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median. There was a significant difference between the Control and 0.3 conditions.

Total SSQ scores

Total SSQ scores differed significantly between the conditions, $\chi^2(2) = 6.07$, $p = .048$. However, *post hoc* tests revealed no significant differences between specific conditions. The Control condition ($M = 33.84$, $SD = 29.05$) did not significantly differ from condition 0.3 ($M = 19.23$, $SD = 16.86$, $p = .062$) or condition 0.6 ($M = 32.06$, $SD = 31.23$, $p = 1.000$). No significant difference was also found between condition 0.3 and condition 0.6 ($p = .316$). The other two SSQ subscales showed similar patterns to the total SSQ scores.

Performance on Maths Task

No significant difference was found between conditions, $\chi^2(2) = 2.20$, $p = .332$. In all conditions, participants answered the questions with high accuracy (Control condition ($M = 97\%$, $SD = 4\%$), Condition 0.3 ($M = 99\%$, $SD = 2\%$), and Condition 0.6 ($M = 98\%$, $SD = 2\%$)).

Reaction Time in the Attention Task

Reaction time was recorded for participants in the attention task. No significant difference was found between conditions, $\chi^2(2) = 5.43$, $p = .066$. In all conditions, participants showed comparable reaction times (in seconds) on the attention task (Control condition ($M = .40$, $SD = .05$), Condition 0.3 ($M = .41$, $SD = .06$), and Condition 0.6 ($M = .39$, $SD = .06$)).

3.2.7 Study 1 Discussion

The preliminary results of Study 1 demonstrate that display manipulation with a coefficient of 0.3 significantly reduced adverse symptoms as indicated by the Nausea subscale of the SSQ. However, no beneficial effects were observed for the other measures. Rotation of the 2D display did not affect performance on the maths task or on the attention task, suggesting that rotation of the display does not notably affect its usability.

One limitation of the study design was that all conditions were conducted within a single day, which may have allowed motion sickness symptoms to accumulate across each condition, potentially affecting the later conditions more than the earlier ones. Efforts to minimize these ordering effects included counterbalancing the order of all conditions. Participants also rated their motion sickness symptoms before each condition using the SSQ to ensure that their reported motion sickness level had returned to baseline, but some accumulation may not have been reported. To address this, Experiment 2 was conducted with all conditions performed on separate days to avoid any accumulation of motion sickness, allowing for validation of results under conditions of lower interference.

The 0.6 coefficient condition did not significantly reduce motion sickness compared to the Control. This outcome may be related to the task plane's reset design; during larger-angle

rotations, the task plane moves to the extreme left or right of the participant's field of view due to the 0.6 setting. When rotation stops, the task plane resets to the center of the participant's field of view, potentially causing additional mismatch between visual and motion information. Future work will explore the causes of this phenomenon and optimize the design, for instance by blinking out the reset rather than having the display move back towards the center. The 0.6 condition was not re-tested in the second experiment due to the extended time required to run experimental conditions on separate days, so only the 0.3 condition was re-tested.

3.3 Study 2: Validation of Rotating Display Cues

In Study 2, the objective was to validate the results of the 0.3 coefficient from Study 1, which significantly reduced the effects of nausea and eliminated any accumulation of motion sickness. Additionally, the effectiveness of motion sickness mitigation was tested using a more complex and motion sickness-inducing set of chair rotations. Each condition lasted 12 minutes, instead of 5. There were two conditions: the Control condition, which was the same as in Study 1, and the experimental condition, which used the 0.3 coefficient. The interval between each condition was extended to 24 hours to prevent the cumulative effect of motion sickness. Figure 3.6 shows the improvements of Study 2. Before each condition, participants completed the SSQ questionnaire to ensure the absence of motion sickness-related symptoms.

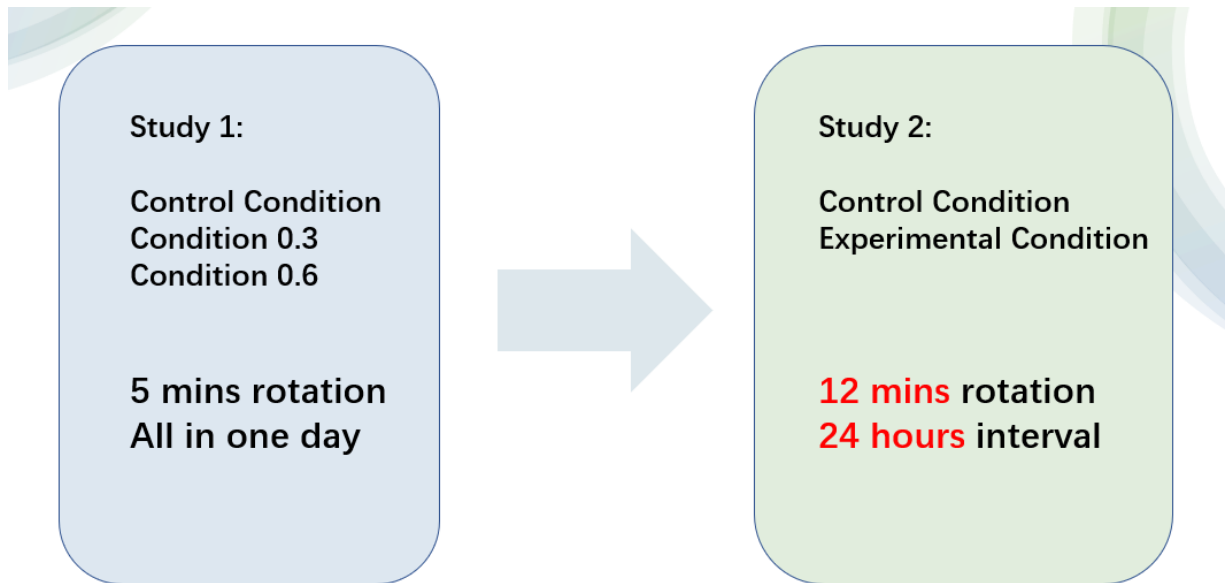


Figure 3.6: Study 2, building on improvements from Study 1, featured conditions with longer durations and larger intervals.

3.3.1 Study Platform

The same rotating chair (*RotoVR*) used in Study 1 was employed as a method to induce motion sickness. The rotation angles and intervals were unchanged. Rotations were scripted using a random function generator to rotate the chair at random intervals of 30, 45, or 90 degrees to the left or right. To provoke more severe motion sickness and validate the design's mitigating effects, the experiment duration was extended to 12 minutes. Additionally, the *Meta Quest 2* continued to be used as the VR platform. Throughout the study, participants wore the VR headset while seated on the rotating chair. This experiment was approved by the University Ethics Committee.

3.3.2 Measurement Method

Motion Sickness Measurement

The same two methods were employed for measuring motion sickness in the second experiment. The primary method was again the Simulation Sickness Questionnaire (SSQ, [78]). Following each experimental condition, participants completed the SSQ to document their experiences and the extent of motion sickness they perceived. The SSQ's scores were utilized to evaluate the intensity of motion sickness among participants. Additionally, a 7-point real-time motion sickness rating slider, cited from [56], was used. This slider was present on the lower part of the VR display throughout the experiment, allowing participants to continuously assess their level of motion sickness. The peak value recorded on the slider represented the highest level of discomfort experienced, while the average value depicted the general status of the participant throughout the experiment. Reminder prompts were shown above the slider approximately every 30 seconds to ensure that participants regularly updated their sickness level. If a participant rated their discomfort at the maximum value of 7 (indicative of moderate nausea), the experiment was halted to safeguard their well-being. Participants were briefed on this protocol prior to the start of the experiment.

Furthermore, the Motion Sickness Susceptibility Questionnaire (MSSQ) [50] was again used to screen participants for their susceptibility to motion sickness. The MSSQ assesses past motion sickness experiences, with the first section inquiring about incidents before the age of 12 and the second focusing on occurrences within the past decade. Participants identified with a frequent history of motion sickness through the MSSQ were excluded from participation.

Productivity Measurement

The second experiment also incorporated a maths task to simulate a productivity measure, involving two-digit addition and subtraction. This task, consistent with prior research, serves as a measure of cognitive function and task load capacity [21, 37]. Participants were required to answer verbally as promptly as possible. The questions refreshed every seven seconds, and

unattempted answers were marked incorrect. The choice of a math task ensured fairness across participants of varied linguistic backgrounds by eliminating disadvantages related to reading speed in text-based tasks [133].

In addition to the primary task, a secondary attention task was administered, requiring participants to activate a trigger on the VR controller whenever a red dot on the screen turned blue. This measure was designed to maintain participants' visual focus on the tasks, drawing from methodologies established by Kooijman et al. [86].

3.3.3 Study Procedure

At the beginning of the experiment, participants reconfirmed that they met all the experimental requirements. They then put on the VR headset and sat on the rotating chair to commence the experiment. The same training session as described in Study 1 was provided to all participants to familiarise themselves with the VR environment and experimental procedure. After completing the training, participants were given two minutes or more of rest until they felt free of any related symptoms of motion sickness. Once the training was completed, participants were assigned to either the control or experimental condition, with counterbalancing employed to minimize interference. After each condition, participants answered the SSQ questionnaire to reflect their symptoms.

3.3.4 Participants

A total of 25 participants were recruited for Experiment 2. Two participants were unable to complete all conditions due to reaching a score of 7 on the motion sickness slider, with one individual completing the experimental condition and the other completing the control condition. Furthermore, one participant was unable to complete the entire experiment due to personal reasons. Their incomplete data were subsequently excluded from the analysis. Thus, complete data from 22 participants, with 11 male and 11 female participants, ranging in age from 21 to 32 years ($M = 24.73, SD = 2.30$) were analyzed. Sixteen of them had some experience with VR. To protect participants, anyone with a history of severe motion sickness was excluded from the study.

3.3.5 Results

Due to the non-normal distribution of the data, the Wilcoxon signed-rank test was used for comparisons. Figure 3.7 shows the results of the continuous motion sickness ratings, displaying the mean reported real-time motion sickness scores of all participants during stimulus exposure for each condition. The sampling rate used was set at 30-second intervals.

Motion sickness slider maximum scores

The maximum level of Motion Sickness reported by participants differed significantly between the Control and the Experimental condition ($Z = -2.77, p = .006$), with participants experiencing stronger symptoms in the Control ($M = 2.72, SD = 1.88$) compared to the Experimental condition ($M = 2.05, SD = 1.70$).

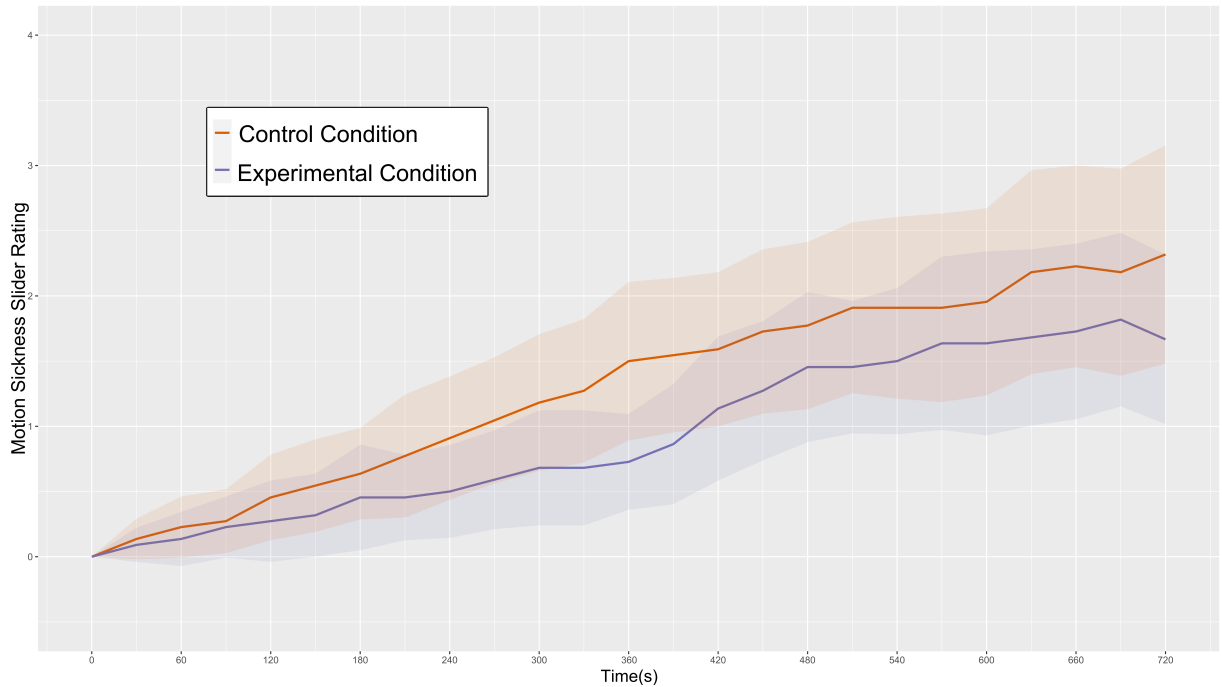


Figure 3.7: Value of the real-time motion sickness slider for the two conditions. The shaded area represents the corresponding confidence interval.

Motion sickness slider average scores

The average level of Motion Sickness reported also differed significantly between the conditions ($Z = -3.10, p = .002$), with participants rating motion sickness higher in the Control ($M = 1.29, SD = 1.07$) compared to the Experimental condition ($M = .92, SD = .89$).

SSQ Nausea Subscale

The scores on the Nausea subscale differed significantly between the conditions ($Z = -3.16, p = .002$), with participants scoring significantly higher on the scale in the Control ($M = 33.82, SD = 22.56$) compared to the Experimental condition ($M = 20.38, SD = 14.21$).

Total SSQ scores

The results of the sub-scale analyses, including Nausea, Oculomotor, and Disorientation, were consistent with the overall SSQ score. Scores on the total SSQ differed significantly between

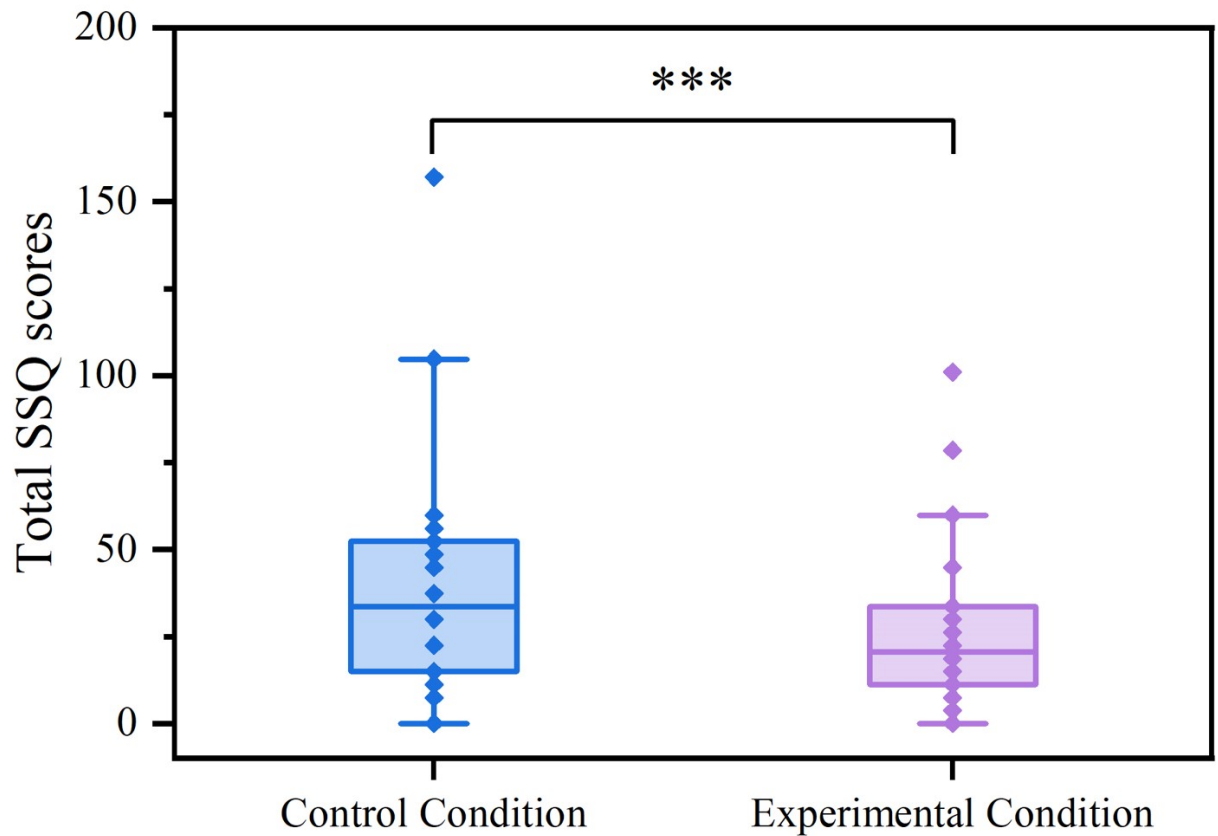


Figure 3.8: The total SSQ scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median. Lower SSQ scores indicate reduced levels of motion sickness.

the conditions ($Z = -3.18, p = .001$), with participants scoring higher in the Control ($M = 42.80, SD = 37.42$) compared to the Experimental condition ($M = 27.03, SD = 27.94$), see Figure 3.8.

Performance on the maths task

No significant difference was found between conditions ($Z = -.75, p = .455$). In both conditions, participants answered the questions with high accuracy: Control condition ($M = 97\%, SD = 3\%$) and Experiment Condition ($M = 96\%, SD = 3\%$).

Reaction Time on the Attention Task

No significant difference was found between conditions ($Z = -.15, p = .884$). In both conditions, participants showed comparable reaction times (in seconds): Control condition ($M = .54, SD = .16$) and Experiment Condition ($M = .52, SD = .12$).

3.4 Limitations

This section represents the first step towards a new type of motion cue that can implicitly convey rotational motion by manipulating planar display content presented in VR. These designs may also be applicable to devices such as AR headsets, but it is essential to evaluate and verify any impacts on effectiveness. However, there are some limitations to this work. Firstly, the studies were conducted using a rotating chair rather than in a real vehicle. Rotating chairs as a common solution can simulate the vehicle's yaw rotation well, but vehicle motion is a complex engineering challenge that also includes pitch, roll, and linear motions. Furthermore, this type of motion may not fully represent the movements that people experience in real vehicles as the city road network consists of various road environments [166], which could potentially lead to more severe symptoms of motion sickness.

For ethical reasons, participants who were likely to be particularly susceptible to motion sickness were screened out. Thus, the studies were likely to only induce mild motion sickness in general. To overcome this limitation in future experiments, longer exposure times or more frequent rotations may be employed. Study 2, building upon this improvements, achieved a higher level of motion sickness than Study 1.

In addition, this implicit cue design is based on the motion of the 2D display itself, which represents an innovative approach but also introduces certain limitations. This design is confined to the 2D display. Although 2D interfaces are widely used in VR applications—such as reading, web browsing, and video playback—it still restricts usage in certain scenarios, such as gaming environments.

Also, due to the relatively low difficulty level of the maths task, the accuracy rate was excessively high. It is speculated that increasing the difficulty level and refining the design of the maths task could make it more demanding for future stress test performance. Besides the maths task, a variety of tasks have been employed in motion sickness research (e.g., reading [134], attention [86]). Future research should consider the suitability and validity of different primary tasks in replicating the cognitive demand expected during typical passenger activities. Furthermore, the performance of methods for implicitly conveying motion will be compared with other explicit visual motion cues, exploring the pros, cons, and trade-offs between implicit and explicit conveyance of motion.

3.5 Overall Discussion

In Study 1, it was discovered that manipulating the motion of a planar 2D virtual display as a visual cue to align with the user's physical motion had a mitigating effect on motion sickness with a rotation coefficient of 0.3. For Study 2, a longer duration of experienced rotation was employed, which induced a higher level of motion sickness symptoms, alongside a more con-

trolled validation approach (one session per day). Under these more rigorous conditions, the cue design was further demonstrated to have a significant effect in reducing motion sickness-related symptoms when the coefficient was set to 0.3.

In the maths task, no significant variations in participants' accuracy levels were observed, indicating that performance on productivity tasks such as this was not compromised by the technique. For the second attention task, across both experiments, participants responded within an average of 0.6 seconds, confirming their ability to maintain an upright posture and focus their attention on the task plane in VR. This underscores that the visual cues designed consistently contributed to alleviating motion sickness in participants. These results preliminarily address **RQ1**. For rotational motion, motion cues can be implicitly conveyed by manipulating the orientation of planar content rendered by an XR device. This implicit conveyance may mitigate the onset of motion sickness and potentially reduce distraction from visual cues. This opens up further research into low-distraction visual motion cues that could be less visually obtrusive than existing cues. Such a design provides a more realistic and immersive simulation for these technologies and helps in identifying more tools to convey motion cues effectively.

This work builds upon previous research [58, 77, 118] that involved manipulating interfaces and content on 2D displays to convey vehicle motion information and extends these findings by demonstrating how such manipulations can be applied in a 3D context to planar content rendered in VR. This approach opens up future research possibilities on how to implicitly convey motion cues and expands the capability to interleave motion cues with planar content. The research findings indicated that using a display rotation with a lesser degree could reduce motion sickness while still enabling participants to see and interact with a maths task presented in a 2D window. The design is applicable to most common 2D planar interfaces rendered by an XR headset, contributing to the improvement of motion sickness mitigation in future autonomous vehicles and enhancing the experience of using VR/XR in self-driving cars.

The visual cue developed in this study is based on manipulating the presentation of existing 2D planar content and does not require additional forms of visual information, such as cityscapes [134] or virtual particles [28], or other overt additional visual or multi-modal motion cues. This allows it to be applied seamlessly to a wide range of existing 2D content, including movies, TV, and 2D productivity apps like (*Immersed*), in VR/XR environments. This approach minimizes the need for extensive additional modifications, accommodating the future demand for using XR devices in vehicles effectively.

Chapter 4

Exploration of Visual Cues for Rotational Motion: Explicitly Cues

4.1 Introduction

In this chapter, the research continues to focus on rotational motion, a common form of vehicle movement. Building on previous studies, using the existing interfaces within the VR environment, low-distraction cues based on implicit conveyance have proven effective. Therefore, this chapter continues to explore methods of conveying motion information through the existing content in the VR environment and compares these methods with some common approaches by using optical flow information cues.

This section introduces the use of the motion of existing elements within the VR environment to convey motion information. It is posited that the brain's cognition of the physical motion of commonly seen objects may offer insights into self-movement awareness and perception. Thus, the physical motion of objects displayed within VR can be utilized to convey the forces experienced in a manner that is familiar to passengers. For instance, swinging items like hanging ornaments or fuzzy dice (see Figure 4.1), commonly found in some car interiors, can serve as intuitive indicators. This method allows for the direct perception of the direction of rotational movement through the motion of elements, hence it is considered an explicitly conveyed cue. Consequently, a physics-based cue was devised that simulates the physical movement of a hanging red ball to convey motion information. Such physics-based cues can seamlessly integrate into realistic virtual reality environments, minimizing distractions. These cues align the visual perception in the virtual environment with the actual physical movement experienced by the vehicle, reducing the incidence of motion sickness. However, the challenge lies in designing these cues to be effective without becoming overly distracting. Ideally, these cues should subtly integrate with the virtual content, ensuring they do not divert attention from essential tasks or overwhelm the user, thus maintaining a balance between comfort and usability. In Study 3, an experiment was conducted to compare this design with a control condition lacking visual cues,

to investigate its effectiveness.



Figure 4.1: An example of fuzzy dice hanging in a vehicle. The way they sway with the physical movement of the vehicle provided design inspiration. Image cited from [120]

After demonstrating the effectiveness of physics-based cues, two additional representative motion sickness mitigation designs were selected for comparison. A multi-session study was conducted using the same rotating chair to analyze the performance of these three designs in terms of mitigation and user distraction. For the first design, the cues employed by Pöhlmann *et al.* [138] were incorporated. This approach involves replacing the entire VR background with a cityscape (or another realistic environment) and conveying motion information through the rotation of the entire background. This method fully occupies the VR background and explicitly communicates both the speed and direction of external motion, along with the degree of rotation, direction of rotation, and optic flow that completely matches physical motion. This condition uses matched motion and is a widely adopted and demonstrated effective visual cue, referred to as the speed-and-direction-based cue (SDBC) in this study. However, this design approach, which requires the use of a complete VR background to display visual cues, has the potential to be distracting and invasive. As an alternative, an explicit direction-based cue (DBC) was also tested, which has previously shown effectiveness in anticipatory motion cue research. Drawing inspiration from the work of Karjanto *et al.* [76], yellow arrows were incorporated within the VR environment to make the motion information more prominent and easily noticeable, thereby enhancing situational awareness.

The study compared the effects of different designs on motion sickness mitigation, ranging from potentially high information density (speed-and-direction-based cue) to lower density

(physics-based and direction-based cue). This comparison was to understand the trade-off between reducing motion sickness and the potential for causing distraction due to visual cues. The experimental results confirm that both the speed-and-direction-based cue and the physics-based cue successfully mitigated motion sickness. Notably, the design incorporating physics-based cues achieved this mitigation with significantly less perceived distraction. By demonstrating the effectiveness of physics-based cues in mitigating motion sickness while minimizing distraction, this research raises questions about the types of visual perception of motion that can resolve sensory conflicts (beyond optic flow-based cues). It opens the door to exploring new ways by which self-motion can be non-disruptively integrated into VR experiences, ultimately aiming to support more productive travel.

Studies in this chapter addresses **Sub RQ1.2** and part of **RQ3**

- **RQ1:** For rotational motion, how is the trade-off between motion sickness and distraction impacted by visual cues resolving sensory mismatch?
 - **Sub RQ1.2** What are the effects of using explicit physics-based cues presenting virtual objects that react to the forces experienced by the vehicle?
- **RQ3:** How to achieve minimally disruptive visual motion cues that balance motion sickness against distraction for Passenger VR?

4.2 Study 3 - Efficacy of Physics-Based Cues

In Study 3, the effectiveness of a physics-based cue (PBC condition) was tested against a control condition (no visual cue) while VR users engaged in a maths task. The PBC condition incorporated physics-based visual cues that are implicitly interpreted as being caused by physical self-motion as we commonly experience them in the real world, for example when the car turns objects hanging from the rear-view mirror move in a similar fashion in response to the car motion. We reflected the external movement through the motion of common items inside the car caused by vehicle turns. The idea is that instead of conveying the absolute motion, we could convey the forces being experienced visually in a familiar yet abstract way.

4.2.1 Study Design

A set of three balls was created that swing in response to external motion. When external motion is detected, the balls sway in the direction opposite to the motion due to inertia. The greater the speed of the external motion, the larger the amplitude of the sway. However, due to the influence of inertia, the amplitude of the balls' sway does not exceed 90 degrees. Once the external motion stops, the balls promptly revert to their initial positions. They are positioned behind the task to avoid obscuring the NDRTs interface, as illustrated in 4.2. The design subtly

conveys information about the direction and speed of external motion through the pendulum movement of the balls. For control, the same design as the PBC condition was used, but with the balls fixed in a stationary position, oriented vertically downwards.

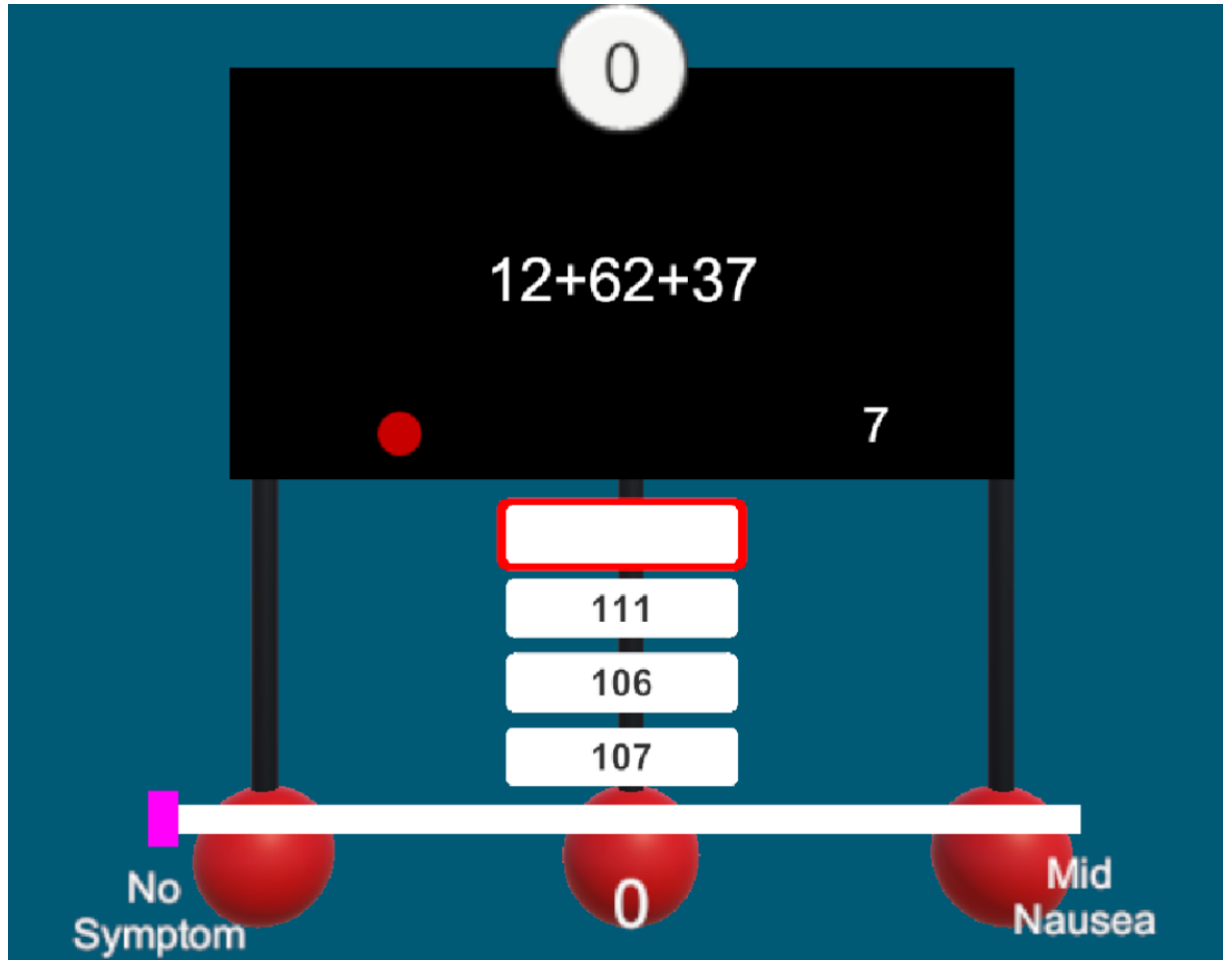


Figure 4.2: Participant's visual experience. The screen presents a mathematics question along with multi-choice answers and a slider for the participant to indicate their current level of motion sickness in real-time. Three red spheres, which form the visual cue, are placed directly behind the VR task area. Their swaying motion constitutes the visual cues.

4.2.2 Study Platform

A rotating chair (*RotoVR*) that can do 1 Degree of Freedom rotation around the yaw-axis was used as a way to induce motion sickness. Participants were seated on the chair whilst wearing a Meta Quest 2 headset, see Figure 4.3. The rotations were scripted by three levels, according to the method detailed in [138]. Rotation speeds were classified as *easy* (≈ 25 degrees per second), *medium* (≈ 35 degrees per second), and *hard* (≈ 45 degrees per second). Each condition was presented for 12 minutes on separate days to avoid cumulative motion sickness effects between conditions. The parameters for the chair rotation in this chapter are more aggressive compared

to the settings in previous sections, meaning they can induce stronger motion sickness. This helps to better test the mitigating effects of visual cues on motion sickness.



Figure 4.3: A participant engages in rotational movements while seated in the *RotoVR* chair.

4.2.3 Measurement Method

Motion Sickness Performance

Two measures of motion sickness were used in Studies 3:

Simulator Sickness Questionnaire (SSQ, [78]) Before and after completing a condition of the experiment, participants completed the SSQ, resulting in an overall measure of motion sickness for the condition;

Real-time 7-point scale motion sickness rating slider This slider, sourced from [56], is displayed beneath the VR task for the entire duration of the experiment. Participants were able to rate their level of motion sickness continuously. To prevent participants from ignoring the slider during the experiment, a reminder prompt periodically appeared above it every 30 seconds. If a participant's rating reached a value of 7, signifying mild-nausea [56], the experiment was terminated to prioritise the safety and well-being of the participant. Participants were thoroughly informed about these thresholds prior to their participation in the study.

Performance and Distraction Performance

Mathematical questions involving two-digit addition were used as the primary task to simulate a productivity activity. Compared to Study 1 and 2, where participants responded verbally to a maths task, the method of answering maths questions was changed to selecting answers using a controller. This adjustment better simulates the actual usage scenario of VR, where users interact via controllers rather than through verbal communication. Similar mathematical tasks have been used in previous research to assess participants' cognitive capabilities and workload capacity [141, 184]. Furthermore, following the approach outlined by Yan *et al.* [184], we categorised the mathematical questions according to their levels of difficulty, allowing us to simulate user scenarios with varying degrees of focus or distraction, thereby enhancing the task's realism. This method involved classifying addition operations with positive integers into seven difficulty levels, considering factors such as the computed result, the number of digits in the addends, and the need for calculating a decimal carry-unit digit. Yan's experiments provided evidence of a linear increase in user computation time as the difficulty levels increased. Accuracy and response time for each question answered by the participants were recorded, reflecting their performance in the productivity activity.

4.2.4 Participants

Twenty-five participants took part in the study. Two participants, one in each condition, dropped out due to severe motion sickness. Two participants were unable to complete all the experiments due to scheduling conflicts, and one participant's data was lost due to technical issues with the application. Resulting in a final sample of 20 participants for data analysis, including 10 females and 10 males, with ages ranging from 22 to 35 ($M = 26.10$, $SD = 3.33$). In the interest of participant safety, those with a history of severe motion sickness were not included in the study based on the MSSQ [50]. Prior to the start of the experiment, participants were asked to reconfirm their eligibility, ensuring they fully met the experimental criteria.

4.2.5 Study Procedure

The experiment consisted of two sessions across three separate days to prevent cumulative effects of motion sickness. The conditions were presented in a counterbalanced order to mitigate potential ordering or learning effects. In the first session, participants were provided with a brief introduction and shown the 7-point motion sickness scale, which they could familiarise themselves with. Following this, the experimenter gave a quick introduction to the VR controls, allowing participants time to familiarise themselves with the controls and tasks. Afterwards, participants engaged in a 2-minute training involving mathematical problems and adjusting the motion sickness slider. During this training, the chair remained stationary to avoid motion sickness. This was followed by a 5-minute break to prepare for the formal experiment. After completing a 12-minute VR condition, participants completed the SSQ to gauge the severity of their motion sickness-related symptoms. This experiment received ethical approval from University of Glasgow.

4.2.6 Results

The Wilcoxon signed-rank test was used for comparisons between the control condition and the physics-based cues condition due to the non-normal distribution of the data.

Continuous motion sickness measure

The maximum value of the continuous motion sickness measure was utilized to reflect the peak discomfort level experienced. The motion sickness level reported by participants differed significantly between the Control and PBC condition ($Z = -2.07, p = .038, \text{Cohen's } d = 0.38$), with participants experiencing stronger symptoms in the Control ($M = 2.60, SD = 1.93$) compared to the Experimental condition ($M = 1.90, SD = 1.71$), see Figure 4.4. The results also indicate that the experimental setup was effective in inducing motion sickness.

SSQ scores

For brevity only the total SSQ (including Nausea, Oculomotor, and Disorientation) score analysis is included here. Scores on the total SSQ differed significantly between the conditions ($Z = -2.65, p = .044, \text{Cohen's } d = 0.55$), with participants scoring higher in the Control ($M = 81.51, SD = 65.81$) compared to the PBC condition ($M = 50.93, SD = 43.17$), see Figure 4.5.

Performance on the maths task

Accuracy in answering mathematical questions was analyzed. No significant difference ($Z = -0.41, p = .679$) was found between the control condition ($M = 93\%, SD = 0.07$) and the PBC condition ($M = 93\%, SD = 0.08$).

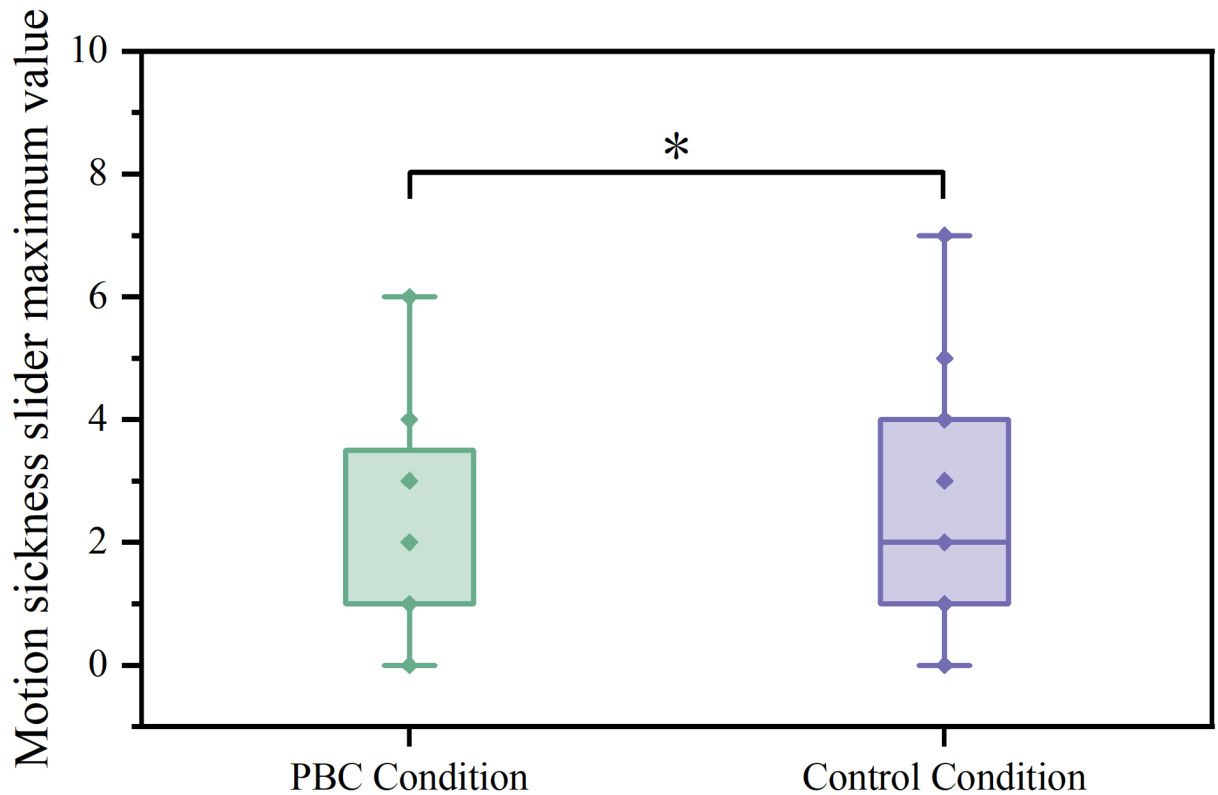


Figure 4.4: Motion sickness value. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.

4.2.7 Discussion

In Study 3, a physics-based visual cue was devised to match physical motion. The results addressed part of **Sub RQ1.2**, validating the effectiveness of the design. Using physics-based visual cues, could significantly alleviate symptoms of motion sickness, as evidenced by both the SSQ scores and the maximum values of the motion sickness slider. This study demonstrated that physics-based visual cues can convey external motion through the actual physical movement of existing elements within the VR environment. This does not explicitly display self-motion information, and if properly designed, does not require additional elements (for example, movement forces could be applied to existing objects within a VR scene), thereby reducing potential distraction.

This study prompted an inquiry into how the PBC (Physics-Based Cue) design compares to common visual cues known to mitigate motion sickness. To address this question, further research and comparisons between different types of cues are necessary. Such comparisons could yield valuable insights into the efficacy of various visual cue designs in terms of mitigating motion sickness and their potential to disrupt the user experience in a virtual environment. Consequently, Study 4 is designed to answer this question by comparing the PBC design with existing, validated visual cues.

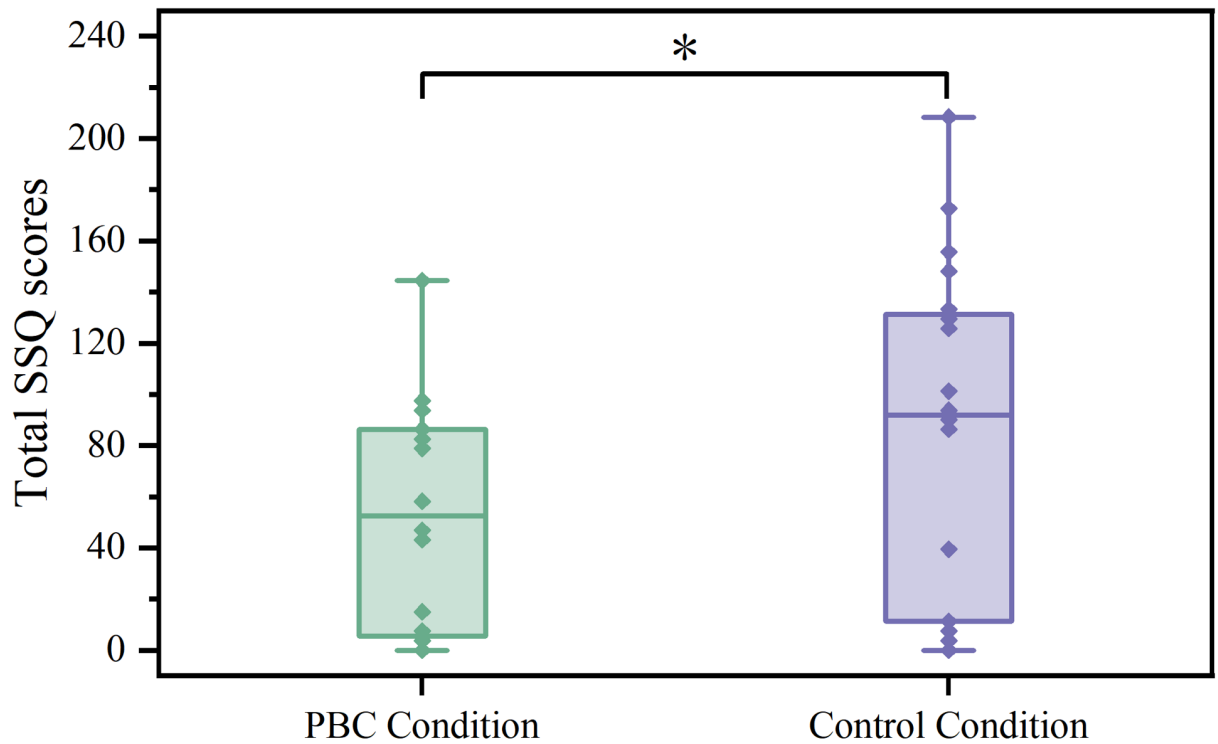


Figure 4.5: Total SSQ scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.

4.3 Study 4 - Comparing Physics-Based Cues with Others

Upon demonstrating the effectiveness of physics-based cues in Study 3, two additional representative motion sickness mitigation designs were identified. Using the same rotating chair, the performance of these three designs in terms of mitigation and user distraction was analysed.

4.3.1 Study Platform

In this study, motion sickness was induced using the same apparatus as Study 3, a rotating chair (*RotoVR*), capable of 1 Degree of Freedom rotation around the yaw-axis. Participants were seated in the chair while wearing a Meta Quest 2 headset. The chair's rotations were scripted into three severity levels according to the specifications in [138]. Each condition lasted for 12 minutes and was conducted on separate days to prevent any cumulative effects of motion sickness.

4.3.2 Measurement Method

Motion Sickness Performance

In Study 4, motion sickness was assessed using two methods. Firstly, participants completed the Simulator Sickness Questionnaire (SSQ, [78]) before and after each experimental condition,

providing an overall measure of motion sickness. Secondly, a real-time 7-point scale motion sickness rating slider from [56] was displayed beneath the VR task throughout the experiment. Participants could continuously rate their motion sickness level. Reminder prompts appeared above the slider every 30 seconds to ensure engagement. If a participant's rating reached 7, indicating mild nausea, the experiment was terminated for safety, with participants fully informed of these thresholds beforehand.

Performance and Distraction Performance

For Study 4, the primary task also employed to gauge productivity involved two-digit addition mathematical questions. This methodological shift aligns more closely with typical VR user interfaces, which predominantly utilize controller inputs rather than voice. Adopting this approach not only reflects the actual usage scenarios in VR environments but also enhances the experimental realism by simulating varied focus levels and interaction complexities.

During Study 3, a high accuracy rate was observed in the two-digit addition task. To increase the difficulty while maintaining the graded complexity of these mathematical tasks, Study 4 introduced an additional digit to the original two-digit addition. This third digit was determined by calculating the integer average of the sum of the first two digits. The design of the tasks is depicted in the right part of Figure 4.3. Accuracy and response time for each question answered by the participants were recorded, reflecting their performance in the productivity activity.

Additionally, in Study 4, a ranking question was designed to subjectively evaluate the degree of distraction caused by the different motion sickness mitigation designs. Participants were instructed to rank the visual cues from the least to most distracting.

4.3.3 Study 4 Design

The study employed a within-subjects experimental design, with motion sickness and productivity measures as dependent variables. The experiment comprised the same physics-based cues condition taken from Study 3 and the following two experimental conditions, with these conditions being presented in a counterbalanced order to mitigate potential ordering or learning effects:

DBC condition: Direction-based cues

This condition incorporates a pair of arrows as a simplified set of visual cues. This design is inspired by Karjanto *et al.* [76], where they alleviated motion sickness by displaying the anticipatory direction of upcoming motion inside a vehicle. The design was integrated into the VR display, with the visibility of the arrows enhanced by changing their color to yellow. This decision was based on previous research findings indicating that yellow turn signals result in significantly shorter reaction times and are widely used in real cars [72], ensuring that they are more

conspicuous and less prone to being missed. Unlike other cues that were not anticipatory, these cues were presented simultaneously as the motion began. When an external rotation is detected, the arrow corresponding to the direction of that motion illuminates. When the motion ceases, the arrow disappears to minimise distraction. This design contains minimal motion information (direction only) and occupies only a small portion of the VR field of view as a visual cue. The study explores whether visual cues that convey limited information—specifically, direction of motion—are effective in mitigating motion sickness. These cues, referred to as Direction-based Cues (DBC), focus solely on indicating the directions of motion. The left panel of Figure 4.6 illustrates this design.

SDBC condition: Speed-and-direction-based cues

This condition incorporates visual cues that simultaneously encompass both speed and direction of motion. The design adopted from Pöhlmann *et al.* [137, 138] incorporated a cityscape view as the VR background. Motion information was conveyed through the rotation of the background. This design uses the entire background as additional display content, aligning the speed and direction information from the background with external motion. Whenever an external rotation is detected, the entire cityscape texture responds with an opposite rotation, presenting optic flow corresponding to the visual motion that would be experienced if participants were not wearing the VR headset experiencing the rotations. Pöhlmann *et al.*'s [137, 138] experiments have demonstrated the effectiveness of such a design in mitigating motion sickness, as depicted in the right panel of Figure 4.6. However, the large amount of visual motion that occurs with this design has the potential to be distracting from a primary task. This design is representative of the current "standard" mitigation strategy [20, 136, 138, 162], and the study compares this established approach with our newly proposed design.

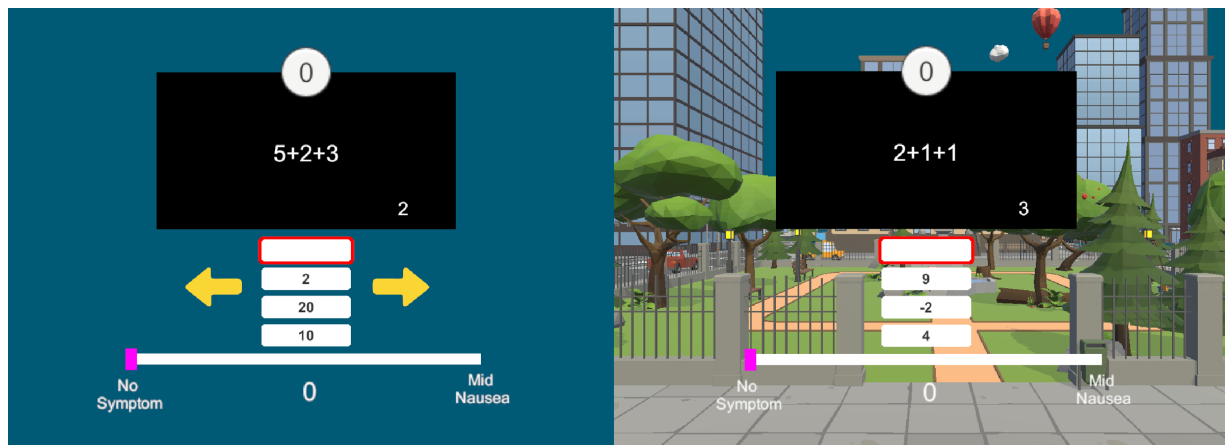


Figure 4.6: On the left is the experimental design for the Direction-based cue condition. On the right is the design for the Speed-and-direction-based cue. Motion information is conveyed through the rotation of the background.

4.3.4 Participants

Twenty-four new participants took part. Only 19 completed all the conditions. Among the 5 participants who did not complete the experiment, one withdrew during the PBC condition, and three withdrew during the DBC condition due to severe motion sickness. One was unable to participate in certain parts of the experiment due to personal reasons. For one participant, who took part in all conditions but withdrew during the last one, we assigned a value of 7 to the subsequent data points on the slider. This value represents the highest possible score. This approach was employed to ensure the integrity of the data to the greatest extent possible [138]. A total of 20 sets of data were used for data analysis, including ten females and ten males, with ages ranging from 21 to 32 ($M = 25.00, SD = 1.80$). In the interest of participant safety, those with a history of severe motion sickness were excluded from the study based on their MSSQ scores taken in advance of the study [50].

4.3.5 Study Procedure

The study was conducted over three sessions across three separate days to prevent potential build-up of motion sickness. The procedural flow of the experiment was identical to the first experiment.

4.3.6 Results

A Friedman's ANOVA was employed, followed by pairwise comparison tests with Bonferroni correction for *post hoc* comparisons among the different experimental conditions.

Continuous motion sickness measure

The development of motion sickness slider ratings over time for the three conditions was compiled and plotted. The maximum value of the continuous motion sickness measure was utilized to reflect the peak discomfort level experienced. Results differed significantly between the conditions, see Figure 4.7, $\chi^2(2) = 9.81, p = .007$. *Post hoc* tests revealed the DBC condition ($M = 2.55, SD = 1.90$) caused a significantly higher level of motion sickness than the SDBC condition ($M = 1.60, SD = 1.27, p = .027, Cohen's d = 0.59$). No significant differences were found between PBC condition ($M = 1.95, SD = 1.84$) and DBC condition ($M = 2.55, SD = 1.90, p = .098$). Also, no significant differences were found between the PBC ($M = 1.95, SD = 1.84$) and SDBC conditions ($M = 1.60, SD = 1.27, p = 1.000$).

Total SSQ scores

Total SSQ scores differed significantly between the conditions, $\chi^2(2) = 15.38, p < .001$, see Figure 4.8. *Post hoc* tests revealed a significantly higher level of motion sickness in the DBC

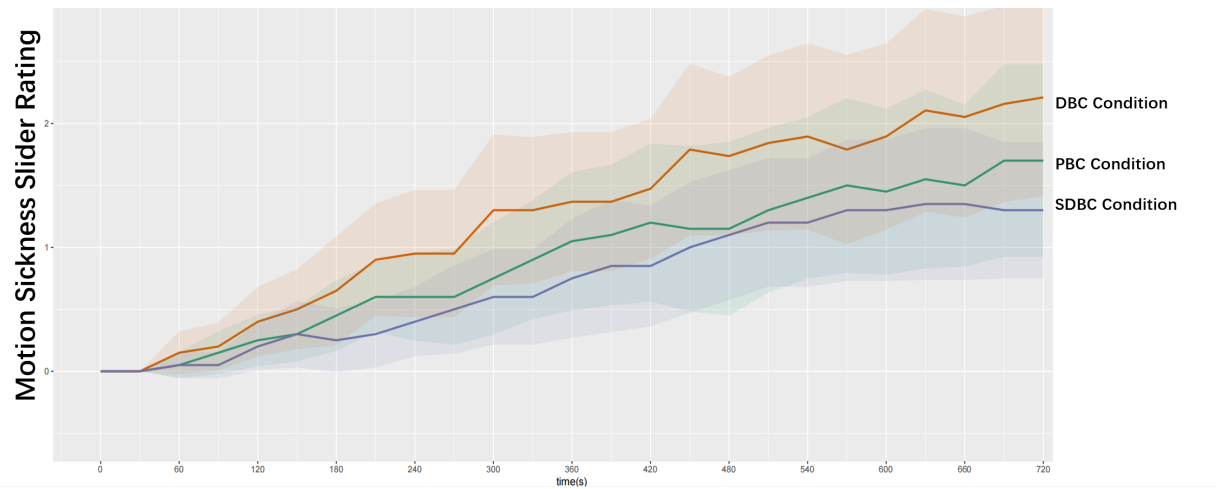


Figure 4.7: Development of motion sickness over time for the 3 conditions rated via the slider displayed in the headset. Shaded areas represent 90% confidence intervals. Y-axis represents Motion Sickness Slider values, participants were able to rate their level of motion sickness: 0: "no problems", 1: "some discomfort", 2-5: "vague to severe dizziness", 6: "little nauseated", 7: "mild nauseated".

condition ($M = 52.17, SD = 43.33$) than the SDBC condition ($M = 24.31, SD = 17.09, p = .005, Cohen's d = 0.85$) and PBC condition ($M = 27.33, SD = 24.45, p = .002, Cohen's d = 0.71$). No significant differences were found between the PBC ($M = 27.33, SD = 24.45$) and SDBC conditions ($M = 24.31, SD = 17.09, p = 1.00$).

Performance and Distraction

A comparative analysis of the PBC ($M = 83\%, SD = 0.82$), DBC ($M = 80\%, SD = 0.70$), and SDBC conditions ($M = 84\%, SD = 0.74$) using the Friedman's ANOVA test revealed no significant differences in maths scores, $\chi^2(2) = 2.80, p = .247$. Our design to increase the task difficulty in the second experiment was successful; we reduced task accuracy from 93% to 84%, thereby avoiding any ceiling effect associated with high accuracy rates.

Participants ranked the three conditions relative to each other in terms of distraction, with Rank 1 assigned to the least distracting condition, Rank 2 to the intermediate, and Rank 3 to the most distracting. Seventeen individuals were included in the final analysis (three participants did not provide responses). A Friedman test revealed a significant difference in rankings across the three conditions, $\chi^2(2) = 10.94, p = .004$, see Figure 4.9. *Post hoc* indicated that conditions PBC ($M = 1.77, SD = 0.66, p = .030$) and DBC ($M = 1.59, SD = 0.71, p = .006$) were significantly less distracting than SDBC ($M = 2.65, SD = 0.70$). No significant difference was found between PBC ($M = 1.77, SD = 0.66$) and DBC ($M = 1.59, SD = 0.71, p = 1.00$).

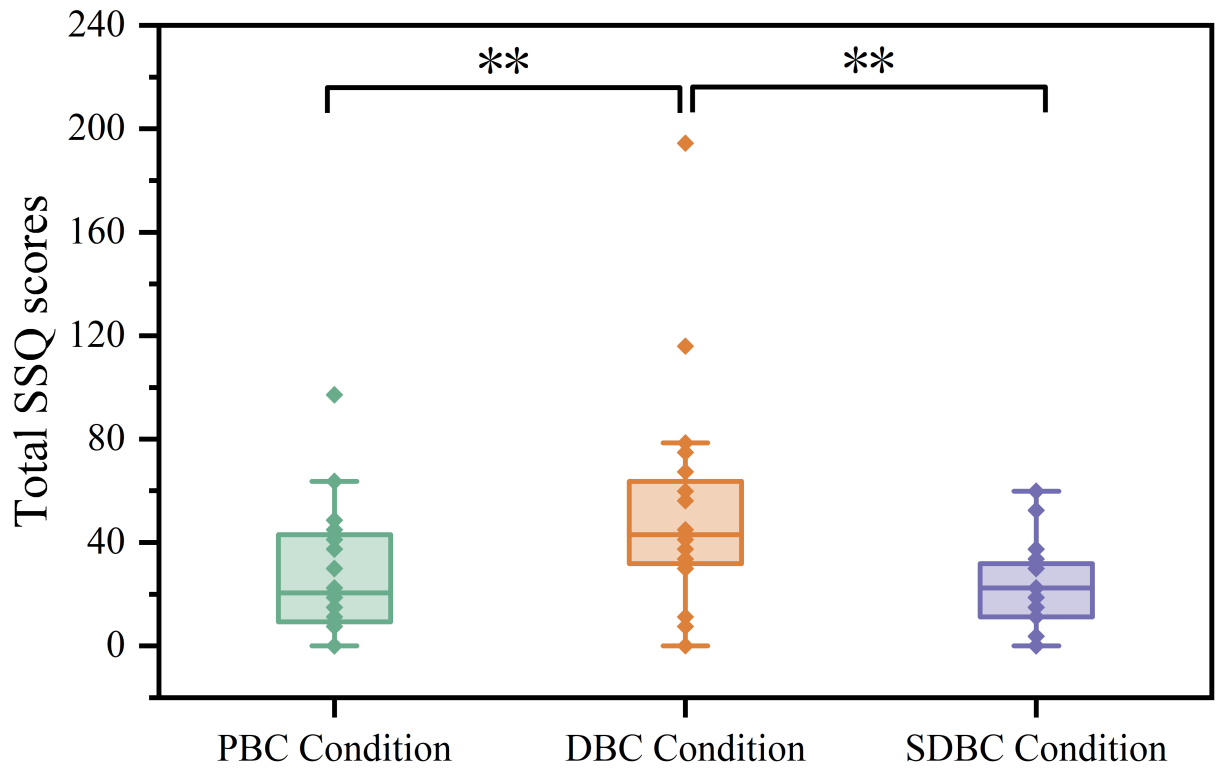


Figure 4.8: Total SSQ scores of study 2, The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.

4.3.7 Study 4 Discussion

Study 3 showed that physics-based cues reduced motion sickness, hence in Study 4, they were compared with the 'standard' mitigation techniques of direction cues and speed-and-direction cues, to compare mitigation levels and to see if they had other benefits, such as lower distraction. Speed-and-direction cues, or matched motion cues, often use VR backgrounds to synchronize fully with external motion and avoid sensory mismatch. Conversely, direction cues convey less information, just presenting direction arrows, but, by exclusively transmitting direction information, potentially alleviate motion sickness while being less distracting.

The results of the SSQ scores collected after each session demonstrate the effectiveness of the design in mitigating motion sickness. Compared to cues based on direction only, cues based on physical motion and those based on both speed and direction significantly reduced the level of motion sickness. The results from the motion sickness slider ratings also confirmed that speed-and-direction cues are better in alleviating motion sickness than direction cues alone. When comparing our physics-based cues with the standard speed-and-direction cues, no significant differences were observed.

Regarding **Sub RQ1.2**, we discovered that both physics-based cues and direction-based cues resulted in lower distraction levels compared to speed-and-direction-based cues. This finding is crucial in VR design: lower distraction implies a better user experience. While SDBC demon-

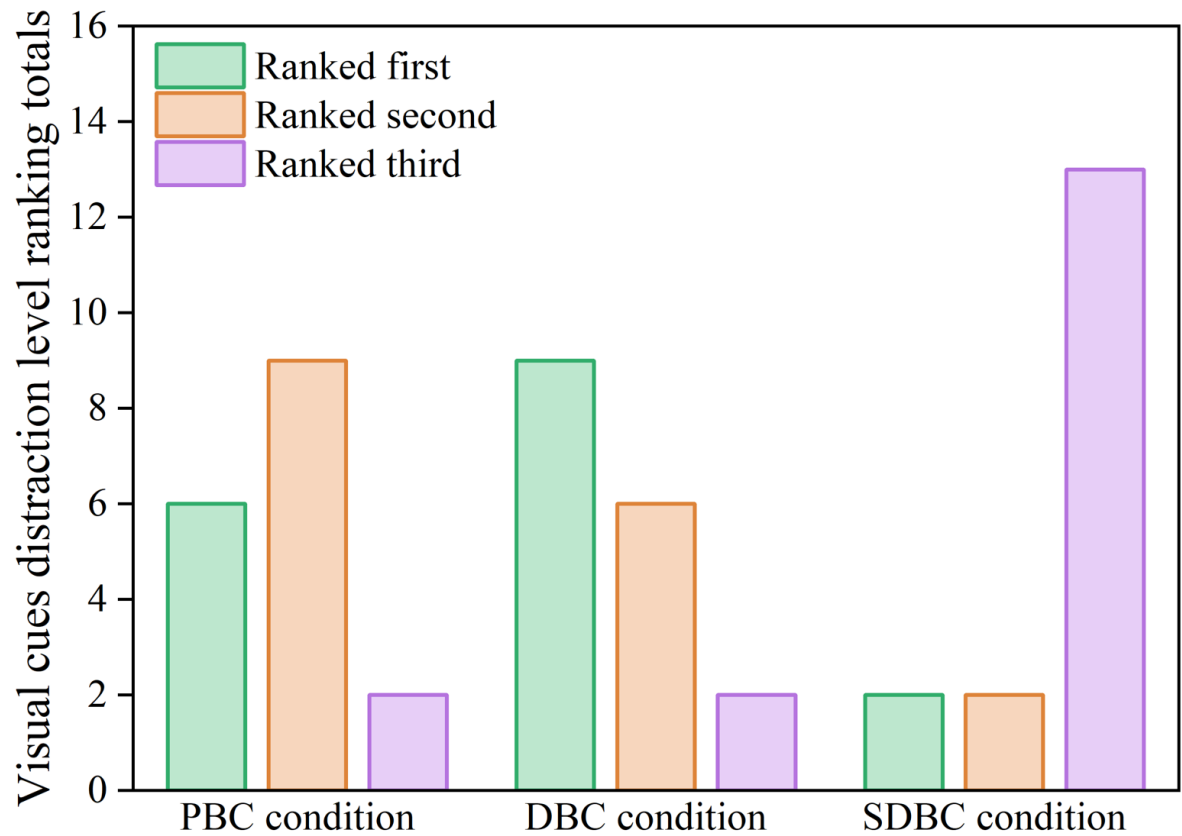


Figure 4.9: Distraction ranking frequencies across conditions ($n = 17$). Bars show how many participants placed each condition 1st/2nd/3rd (Rank 1 = least distracting; Rank 3 = most distracting).

strated the best motion sickness mitigation performance in the experiment, they also introduced the highest level of distraction. Our physics-based cues provide a good compromise, with lower distraction and strong mitigation performance.

4.4 Limitations

There are some limitations to this study. The study was conducted on a rotating chair, The chair allowed for more precise control of motion to ensure that each participant experienced the same motion stimuli. This provides a clear baseline of performance for the different cue types. The motion profile of the chair was however limited to yaw rotation and could not induce linear forward and backward motion or roll and pitch rotations, which could be experienced in more advanced motion simulators or during travel in a vehicle.

Additionally, this research on participant distraction is relatively limited. Unlike motion sickness, there is no unified approach for studying user distraction. The task performance and subjective ranking questions we employed may not fully reflect the distraction caused by visual cues on users. More objective methods, such as eye-tracking technology, can be used to

investigate this more effectively in the future.

4.5 General Discussion

4.5.1 Efficacy of Physics-based Cues in Motion Sickness Mitigation

Through two studies in this chapter, the significant mitigating effects of physics-based cues on motion sickness were validated. By integrating the results of both studies, it was observed that purely directional information was less effective. However, physical cues provided sufficient information to achieve mitigation effects comparable to those of speed-and-direction-based cues, which offer comprehensive motion information and show full optic flow outside of the VR headsets. While speed-and-direction-based cues have been extensively validated and implemented by peers [69, 136, 138], cues based on physical characteristics are novel and have been proven effective for the first time. Such cues do not need to dominate the entire VR background and, if well designed, can convey motion information without distraction while integrating with physical movements within the VR environment.

4.5.2 Physics-based Cues Mitigate Motion Sickness whilst Minimizing Disruption

Accuracy in the maths task did not change across conditions, suggesting that the cues may not have a strong distraction effect on the task. It might, however, be due to the fact that the maths tasks were relatively easy, which resulted in good task performance. However, based on the subjective rankings of distraction levels across different conditions, the SDBC condition, which utilised the entire background as a visual cue, was perceived as significantly more distracting than both the Physics-based and the Direction-based conditions.

The effectiveness of visual cues in mitigating motion sickness has been discussed in previous research. However, the aspect of distraction caused by these cues has not been thoroughly investigated. The physics-based, PBC condition was designed to strike a balance between these two aspects. It approaches the mitigation effectiveness of widely used methods (such as the SDBC condition) while providing lower distraction, potentially creating a higher level of user comfort.

4.5.3 Integrating Visual Cues in VR to Enhance Motion Perception and Reduce Motion Sickness

This chapter opens the door to a breadth of visual cues that could be better integrated into the VR environment or potentially manipulate things already in the VR scene and answers part of **RQ3**. By integrating the motion of objects within the VR environment as visual cues into VR

spatial UIs, it is possible to effectively achieve non-disruptive visual motion cues that balance motion sickness alleviation against distraction.

This design principle is effective not only for the rotational movements explored in our chapter but also may benefit other types of vehicular motion, such as linear movement. Examples include the swaying of water on a table in response to vehicle movement when the user is situated in a productive environment, or the movement of tree and plant leaves in a jungle environment in reaction to vehicle motion, as opposed to the vehicle's absolute velocity. Such an approach does not need to add any extra objects to the scene for mitigation. Through these carefully considered designs aimed at reducing motion sickness, the integration of VR devices into vehicles will become an essential aspect of travel, transforming the passenger experience in cars, planes, buses, or trains into an immersive virtual space, ultimately enhancing the overall passenger experience.

Finally, when we consider the prevailing theory of sensory conflict resulting in motion sickness, this work provokes new considerations of what constitutes appropriate visual stimuli to resolve this conflict. Past research has focused on optical flow and matched motion-type experiences as absolute conveyances of the physical motion being experienced. However, in demonstrating that a physics-based cue is effective, this suggests that the physics-based calculations our brain [41] is making when viewing these cues could form part of the multi-sensory integration of available motion cues in determining the overall motion being experienced - raising fundamental questions for future research around what constitutes effective visual motion cues when considering sensory conflict and motion sickness.

Chapter 5

Exploration of Visual Cues for Linear Motion

5.1 Introduction

In previous chapters, visual cues based on yaw rotational movements have been explored. However, when driving on real roads, such as city streets and highways, the vehicle undergoes significant linear motion, including acceleration, deceleration, and steady-speed travel. Therefore, linear motion is also a fundamental type of vehicle movement. This chapter focuses on studying visual cues for linear motion. To better examine linear motion absent significant rotational motion, the studies in this chapter have been prepared using a pre-defined near-straight real-world car route.

Mainstream in-car motion sickness studies have used *matched motion* to align virtual environments with real vehicle movements—such as velocity and rotation—to ensure consistent sensory perceptions of self-motion to alleviate motion sickness [138, 139]. According to the sensory conflict theory, aligning these sensory inputs will alleviate motion sickness [77, 124]. While *matched motion* can mitigate motion sickness, cues might detract from the overall user experience by diverting attention and causing distraction from the media content or NDRT the passenger is trying to perform [109, 136, 188]. In psychological studies on distraction, it is typically defined as factors that interfere with an individual’s ability to complete a primary task [148]. This interference can arise from multitasking or external stimuli [163]. In highly immersive VR single-task studies, users’ sensory input is confined to the visual elements within the virtual interface, making any non-task-related visual stimuli potentially disrupting, referred to as visual interference [163]. For example, human peripheral vision is highly sensitive to motion [109]. Thus, any moving visual element can involuntarily draw a user’s gaze or focus away from their primary activity. While visual cues are essential for conveying motion information to alleviate motion sickness, they inherently compete for attentional resources with media content and can cause distraction if not designed carefully. In real-world driving scenarios, such as

navigating city streets or highways, the vehicle undergoes substantial motion, including acceleration, deceleration, cruise, and turns, meaning the user will experience constant visual motion cues, which can be distracting. This is due to the motion of elements composing the visual cues generating substantial optic flow information, which could capture user attention and introduce distractions from the NDRTs that the user wishes to engage with. Thus, designers must balance adding visual motion cues against the risk of distraction from the main VR content.

In contrast to the visual system providing constant information about velocity, the vestibular system primarily detects changes in velocity, specifically acceleration or orientation [14]. Hence, the chapter investigates the novel acceleration-based motion cues which align closely to the self-motion detected by the vestibular system, rather than matching the expected self-motion detected by the visual system. They are delivered through the movement of a stereoscopic optic flow stimulus in VR, specifically linked to the vehicle's acceleration rather than its absolute velocity. To achieve this, an optic flow stimulus, virtual starfield, was developed, which simulated a three-dimensional cloud of red spheres (Red cues in VR can make visual stimuli more prominent [143]). This stimulus affords us the flexibility to design and deploy dynamic visual cues and has been applied in many research [19, 121, 122]. For instance, as the vehicle accelerates from a standstill, the starfield moves backwards, simulating the sensation of self-forward motion; as the vehicle stabilizes at a constant velocity, the starfield halts, reflecting no perceptible motion; and when the vehicle decelerates, the starfield moves forward. This approach is anchored in sensory conflict theory, aiming to synchronize the visually perceived motion with the acceleration detected by the vestibular system rather than matching it to the visual motion perceived in reality. A simple starfield-based acceleration cue [3] has recently been deployed to iOS devices as a motion sickness countermeasure, but the size of the mobile display means that the cues overlap with content and thus are potentially distracting. Mobile display size limitations mean the cues presented do not reach peripheral vision, where they would be most beneficial [15]. Acceleration cues offer a potential improvement over matched motion cues as they may resolve sensory conflict in ways that require less perception of visual motion, and consequently less distraction and disruption (e.g. having no visual movement when the car is at a steady speed). Additionally, accurately matching the VR scene's motion with actual vehicle velocity often necessitates extra effort such as additional hardware [47, 61, 111] or employing GPS to estimate vehicle velocity [19, 20]. These add cost, complexity and encounter issues with positional drift [111] over time. For acceleration, an off-the-shelf inertial measurement unit, commonly found in devices such as phones, is sufficient.

The research encompasses two on-the-road studies (Study 5 and Study 6) conducted in daily traffic. In Study 5, participants engaged in three sessions using real vehicles on a predefined urban route. This study compared conditions using acceleration-based cues (with a starfield background) with matched motion cues (with a cityscape background) and no motion cue baseline (with a cityscape background). The objective was to evaluate the effectiveness of acceleration

in reducing motion sickness and to ascertain the potential distractions caused by the visual cues. Results from Study 5 indicated, for the first time, that acceleration cues can mitigate motion sickness and even perform similarly to the most "effective" mitigation cues (cityscape matched motion).

Subsequently, Study 6 build upon the work of Study 5 by specifically investigating the differences in distraction and disruption between matched motion and acceleration-based cues. Since Study 5 was preliminary, as it used different backgrounds for each condition, making it difficult to compare results across conditions to see the benefits of acceleration based cues on motion sickness or distraction. Recent research has shown that even when the same visual cue motion strategy is applied, users exhibit different preferences and levels of distraction depending on the background design [121], which limited the exploration of visual cue distraction. Hence, Study 6 builds on this by further comparing matched motion and acceleration based cues using the same design, particularly for distraction. Reducing distraction is a significant potential advantage of designing such cues, making further investigation in this area crucial.

In Study 6, a uniform starfield background was applied across all conditions, enabling a more rigorous comparison under consistent visual cue elements. The starfield background, being less constrained by realistic scene design compared to an urban background, offers greater flexibility for experimentation. Also, for linear motion, applying gain or attenuation to visual cues does not significantly increase motion sickness [139]. This allows designers greater freedom in controlling the speed of visual motion in VR applications, without being strictly constrained by real-world motion parameters. This was also tested with acceleration cues for the first time, by including an additional condition in our study to investigate the effects of applying a 2x gain to the starfield displays to see its effects on motion sickness and distraction. Through these comparisons, the performance of acceleration-based cues in terms of motion sickness mitigation and distraction compared to *matched motion* cues were systematically investigated, as well as the impact of gain on distraction levels.

The results indicate that acceleration-based cues resulted in similar levels of motion sickness as velocity-based matched motion cues, which are the gold standard in motion sickness mitigation to date, while being perceived as less distracting. Applying gain to the acceleration-based cues did not diminish their effectiveness in mitigating motion sickness, nor did it affect performance on certain distraction-related measures, indicating that gain could be effectively utilized for such cues. Our research provides novel insights into how alternative types of visual motion perception, beyond traditional matched motion cues, can enhance the travel experience for passengers without inducing motion sickness symptoms. Ultimately, this work will facilitate more comfortable and enjoyable travel, broadening the potential for VR-based applications in transportation

5.2 Study 5 - Efficacy of Velocity and Acceleration-Based Cues

In the Study 5, we examined the effects acceleration-based cues and velocity-based cues have on motion sickness and distraction while performing a VR video task in a moving vehicle. **Sub RQ2.1** in **RQ2** was covered by Study 5:

- **RQ2:** For linear motion, how is the trade-off between motion sickness and distraction impacted by visual cues that resolve sensory mismatch?
 - **Sub RQ2.1** Can acceleration-based visual cues reduce motion sickness?

5.2.1 Study Design and Setup

The study used a within-subjects design with motion sickness level, user experience ratings and task performance as dependent variables. There were three conditions: *Acceleration*, *Velocity*, and *Control*.

Acceleration Condition

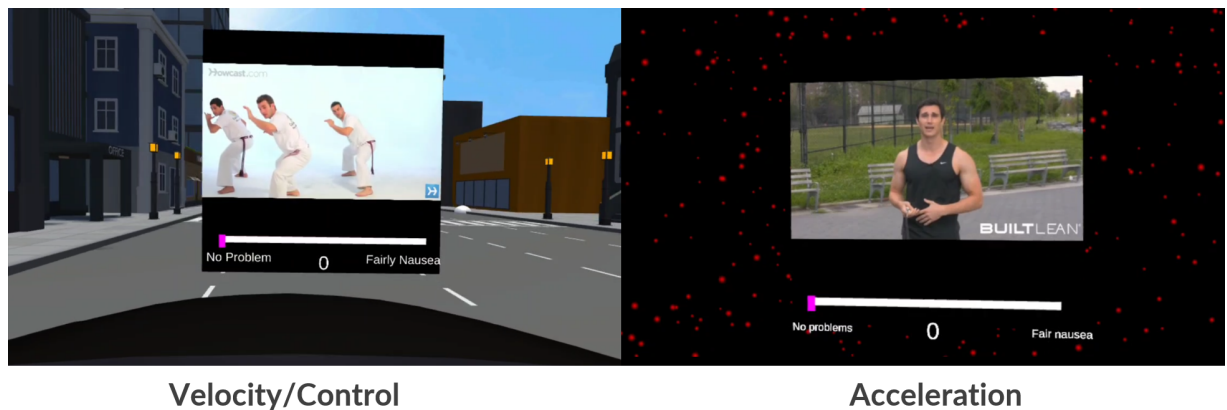


Figure 5.1: On the side are screenshots of what the participant sees, with the left portion representing the Velocity/Control condition. The background of the former will move with the velocity of the vehicle, while the background of the latter is static. The right portion shows the starfield used in the Acceleration condition. The size and position of the task plane remained constant across conditions, though differences in VR screenshots may arise from varying angles or vehicle motion.

A virtual starfield display was developed, which simulated a three-dimensional cloud of red spheres as depicted in the background of Figure 5.1 right, serving as the foundation for the visual cue design. Similar designs have previously been utilized in non-VR [33, 40] and VR-related motion sickness studies [59, 81], but not specifically for acceleration. Participants were immersed in this dynamic environment while engaging in a video-watching task centrally

positioned within their visual field. The three-dimensional arrangement of these particles provides a dynamic and immersive visual environment essential for simulating real-world motion in VR. Furthermore, the flexibility of the starfield design enables precise manipulation of motion parameters such as velocity and acceleration. Similar starfield configurations have been previously adopted in both non-VR [33, 40] and VR motion sickness studies [59, 81]; however, their application in acceleration-based cues has not been widely explored. Recent technological developments, such as Apple’s *Vehicle Motion Cues* in iOS 18 [3], which employs particle-based motion visualization to alleviate motion sickness, provide practical validation for this concept.

The virtual starfield was generated using a particle system in Unity3D, continuously spawning randomized red particles. The motion of the starfield was directly correlated with vehicle dynamics: particles moved backward or forward at a speed corresponding precisely to the vehicle’s real-time acceleration or deceleration. When the vehicle maintained a constant velocity or remained stationary, the starfield stayed static, accurately reflecting zero acceleration. Figure 5.2 illustrates the motion of the starfield in these three conditions through animated form. This design subtly conveys the vehicle’s motion through acceleration cues, potentially causing less distraction compared to traditional velocity-based matched motion designs.

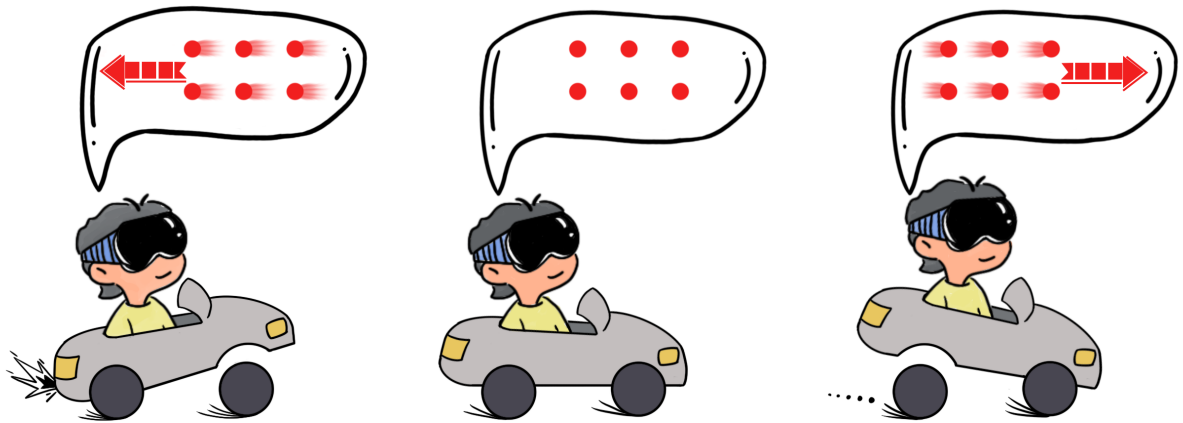


Figure 5.2: The motion patterns of the starfield are displayed in animated form. On the left, as the vehicle accelerates, the starfield moves backward (opposite to the direction of the user’s forward view); in the middle, as the vehicle moves at a constant speed, the starfield remains static; on the right, as the vehicle decelerates, the starfield moves forward.

Velocity Condition

For comparative purposes, the velocity condition employed a matched motion design where the backward movement velocity of a virtual city background was regulated based on the vehicle’s velocity, obtained from the car’s OBD interface, as illustrated in Figure 5.1 left. A virtual city background was chosen to closely mimic the real-world passenger experience [139]. This background included straight urban roads surrounded by offices, houses, shops, and pavements, with the scale of the buildings and the parameters of the roads set to closely match the environ-

ment surrounding the experimental road. This design ensures that the velocity condition closely aligns with commonly used matched motion cues and is capable of eliciting a strong sensation of self-motion [139].

Control Condition

In the control condition, there was no representation of vehicle motion. The same city design from the velocity condition was used, but with the city background fixed in a stationary position, representing the scenario with no visual cues. This condition was likely to cause the highest motion sickness as there was no visual cue to indicate vehicle motion.

5.2.2 Experimental Platform



Figure 5.3: The participant is shown wearing a VR headset while seated in the vehicle for the experiment. On the left side of the image, an experimenter is present to assist the participants.

Two different vehicles—an SUV (KIA Niro) and a Saloon/Estate (Skoda Superb)—were rented during the study. Each vehicle was assigned an equal number of participants. Participants were seated in the rear left seat of the car and were instructed to watch videos and answer video-related questions while wearing a Pico 4 Pro VR headset. Figure 5.3 displays a scene from the

experiment, showing a participant wearing a VR headset in the car. There was a driver to control the vehicle and an experimenter to assist participants. For the Velocity condition, we used the PassengXR platform [111], see Figure 5.4 to capture vehicle velocity. For other conditions, all the vehicle movement data was collected by a VR controller mounted in the car (which contains an IMU suitable for detecting acceleration).

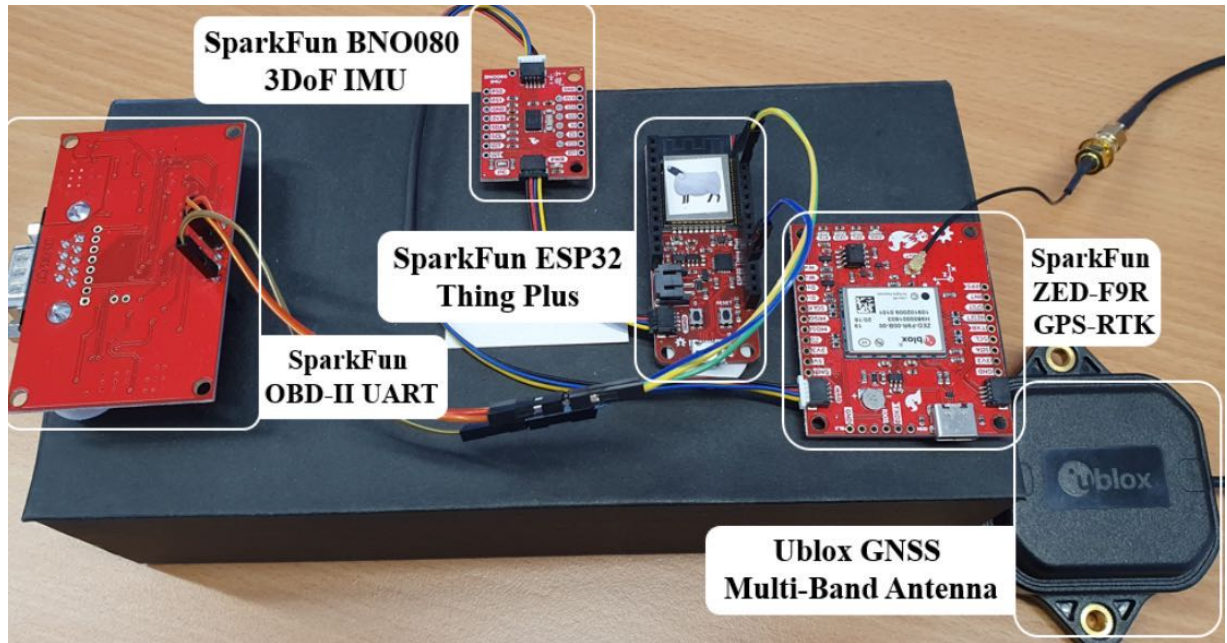


Figure 5.4: The schematic of the PassengXR Open-Source Motion Platform is composed of multiple parts; for this experiment, only the functions of the ESP32 and OBD units were utilized.

5.2.3 Driving Route

The vehicle traversed a 2-mile stretch of city road, averaging 16 minutes per journey, with a speed limit of 30 mph, as depicted in Figure 5.5. Conducting the experiment on real roads increased ecological validity. As rotational and linear motion are detected by different parts of the vestibular system, and since rotational motion has been extensively studied with rotating chairs [138, 179], a straight road was selected to minimize the influence of curves. This approach allowed the focus to remain on linear motions, including acceleration, deceleration, and steady speed. The study of motion sickness induced by linear motion on straight roads has been less explored, largely due to the greater demands for experimental platforms. By distinguishing these two types of motion, the research could investigate linear motion in isolation, and effectively validate the design's effectiveness. Additionally, the experiments were scheduled between 10 AM and 4 PM to avoid the variable of peak traffic congestion, ensuring more consistent conditions.

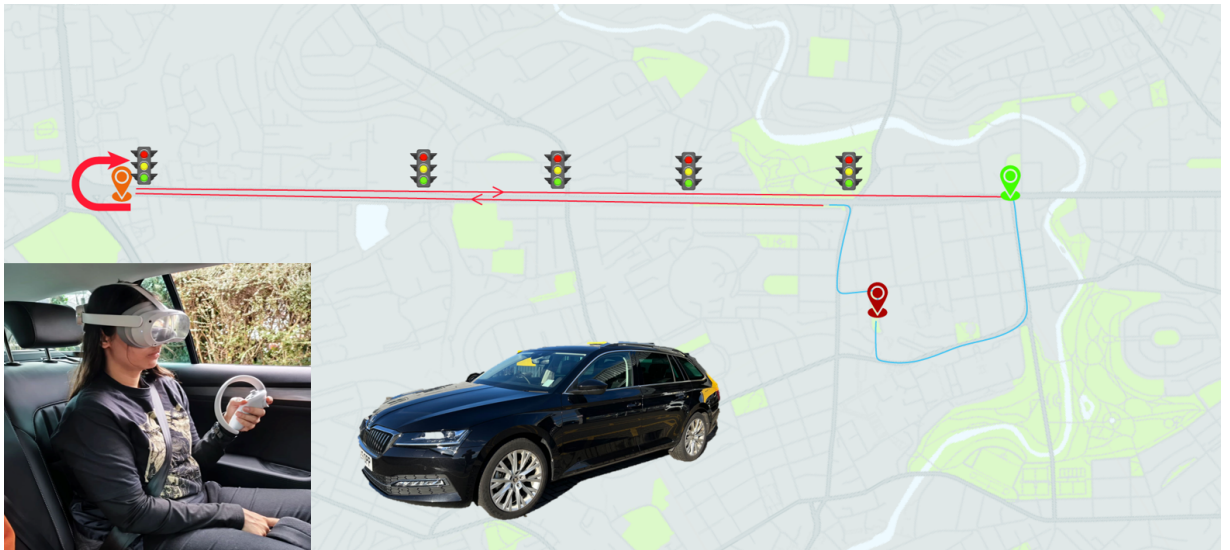


Figure 5.5: Road taken during Studies 1 and 2. The red line indicates the straight road used in Study 1. The blue line represents the additional curves near the starting and ending points of the route, which were included in Study 2. The red dot is the start point of studies

5.2.4 Measurements

Motion Sickness

Two measures of motion sickness were used in Studies 3:

Simulator Sickness Questionnaire (SSQ, [78]) Before and after each condition, participants filled in the Simulator Sickness Questionnaire (SSQ) [78], providing an overall measure of motion sickness for each condition;

Real-time 7-point scale motion sickness rating slider This slider, sourced from [56], is displayed beneath the VR task for the entire duration of the experiment. Participants were able to rate their level of motion sickness continuously. Participants were required to adjust the numerical value using a joystick based on the definition of the MISC slider whenever they perceived a change in their motion sickness state. If a participant's rating reached a value of 7, signifying mild-nausea [56], the experiment was terminated to prioritise the safety and well-being of the participant. Participants were thoroughly informed about these thresholds prior to their participation in the study.

Since our design's primary intent is to reduce the potential distractions caused by motion sickness mitigation cues, at the end of the experiment, participants were instructed to rank the distraction level of visual cues across the three conditions (from lowest distraction to highest distraction).

Video Task Performance

Participants viewed six two-minute video clips, answering four related questions per clip within a 10-second time limit per question, see the video figure for examples of the task and conditions. The video clips were played sequentially without any pauses in between. These videos and questions were sourced from the ActivityNet database [186], a widely used benchmark in computer vision containing annotated Question/Answer (QA) pairs. We employed them as watching videos is a very common activity during travel [2], and we could measure comprehension via a simple set of questions. We selected videos from the dataset with minimal on-screen motion to prevent any visually induced motion sickness. Each video in the database is associated with ten QA pairs. After screening the pairs to ensure no prior knowledge was required and difficulty was appropriate, we conducted an online test on Prolific ($n = 100$ in total, for each video, $n = 20$). Each online participant viewed six videos, consistent with the experiment setup, and responded to the accompanying QA pairs using a multiple-choice format. Based on the accuracy rates for each QA pair obtained from the online test, we selected four pairs per video to achieve an average overall accuracy rate of approximately 80% for the questions associated with each video. This accuracy rate was calibrated to ensure that the task was neither overly challenging—potentially leading to participant frustration—nor excessively simple, which could induce boredom during video viewing. Additionally, the presentation order of the videos was counterbalanced to avoid the impact of cognitive load and attention on motion sickness and task accuracy.

Subjective Distraction

We implemented subjective measures to evaluate visual distraction. Participants completed a subjective ranking questionnaire at the experiment’s conclusion, ranking distraction levels induced by visual cues across the three conditions from lowest to highest.

5.2.5 Participants

Twenty participants took part in the study. One participant dropped out as the MISC rating reached 7 during the Control condition, leaving 19 complete data points, including 10 females and 9 males, with ages ranging from 19 to 35 ($M = 23.90$, $SD = 3.85$). To ensure participant safety, individuals with a history of severe motion sickness (Motion Sickness Susceptibility Questionnaire total scores over 30 [49]) were excluded from the study.

5.2.6 Study Procedure

The experiment was conducted over three separate days, with one session per day, to prevent cumulative effects of motion sickness. To minimize potential ordering or learning effects, the conditions were presented in a counterbalanced order. In the first session, participants received

a brief tutorial on the VR controls followed by a 3-minute training session that included a video and related questions. All training was conducted while the vehicle remained stationary to mitigate the onset of motion sickness. After a 5-minute break, the formal experiment began. Each experimental condition lasted 16 minutes, subsequent to which participants completed the SSQ and other questionnaires to assess the severity of their motion sickness symptoms and their level of immersion in the VR conditions. The studies in this paper received ethical approval from our University's Ethics Committee.

5.2.7 Results

A single-factor Friedman's ANOVA was employed, followed by pairwise comparison tests with Bonferroni correction for *post hoc* comparisons between the different experimental conditions. When the data for each vehicle were analyzed, the results were consistent, suggesting that the type of vehicle used did not differentially affect motion sickness.

Continuous motion sickness measure

The maximum MISC score selected by the user in each condition was used to reflect the peak discomfort level experienced. Results differed significantly between the conditions, see Figure 5.6, $\chi^2(2) = 11.61, p = .003$. *Post hoc* tests revealed the Control condition ($M = 2.84, SD = 1.90$) caused a significantly higher level of motion sickness than both the Acceleration ($M = 1.58, SD = 1.64, p = .036$, Cohen's $d = 0.71$) and Velocity conditions ($M = 1.52, SD = 1.39, p = .028$, Cohen's $d = 0.79$). There was no significant difference between Acceleration and Velocity conditions ($p = 1.000$).

Total SSQ scores

As all three sub-scales (Nausea, Oculomotor, Disorientation) yielded results similar to the total SSQ scores, only total scores are reported for brevity. Total SSQ scores differed significantly between the conditions, $\chi^2(2) = 25.73, p < .001$, see Figure 5.7. *Post hoc* tests revealed a significantly higher level of motion sickness in the Control condition ($M = 50.77, SD = 33.55$) than the Acceleration ($M = 17.41, SD = 20.37, p = .000$, Cohen's $d = 1.20$) and Velocity conditions ($M = 18.86, SD = 16.18, p = .000$, Cohen's $d = 1.21$). There was no significant difference between Acceleration and Velocity conditions ($p = 1.000$).

Task Performance

No significant differences in video question accuracy were found between conditions, $\chi^2(2) = 4.91, p = .086$. The results were: Acceleration condition ($M = 66.0\%, SD = 0.12$), Velocity conditions ($M = 73.0\%, SD = 0.08$), and Control condition ($M = 66.6\%, SD = 0.92$).

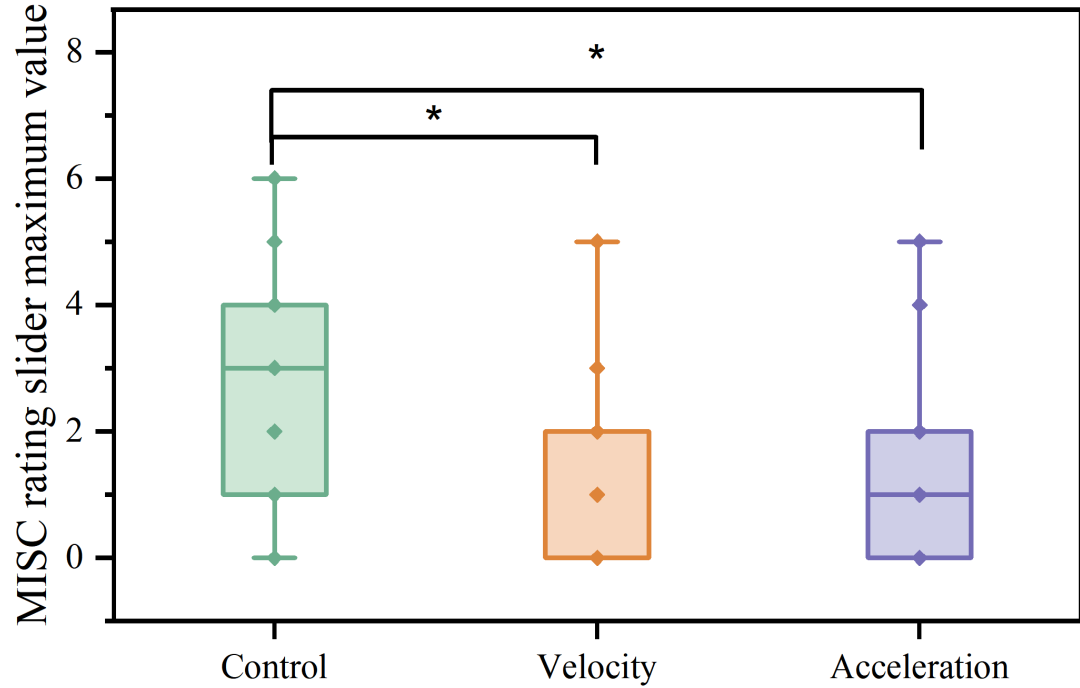


Figure 5.6: The MISC maximum value. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median. Lower MISC scores indicate reduced levels of motion sickness.

Distraction and User Experience

The rankings of the two motion sickness mitigation designs were compared by assigning a value of 1 to conditions that were ranked at a higher level of distraction, and -1 to conditions that were ranked at a lower level of distraction. A condition's average value closer to 1 indicates that it was more frequently selected as the most distracting condition. The final results showed that the Velocity condition had a higher distraction rating ($M = 0.47, SD = 0.90$), while the Acceleration condition ($M = -0.47, SD = 0.90$) had lower distraction levels, ($\chi^2(2) = 4.26, p = .039$, Cohen's $d = 1.05$).

5.2.8 Study 5 Discussion

The experimental results demonstrated that the acceleration-based cue significantly reduced motion sickness compared to the Control condition, as evidenced by both the SSQ and MISC scores. This validated the effectiveness of presenting acceleration cues for alleviating motion sickness. When comparing this design to the 'standard', velocity-based cue, both achieved similar out-

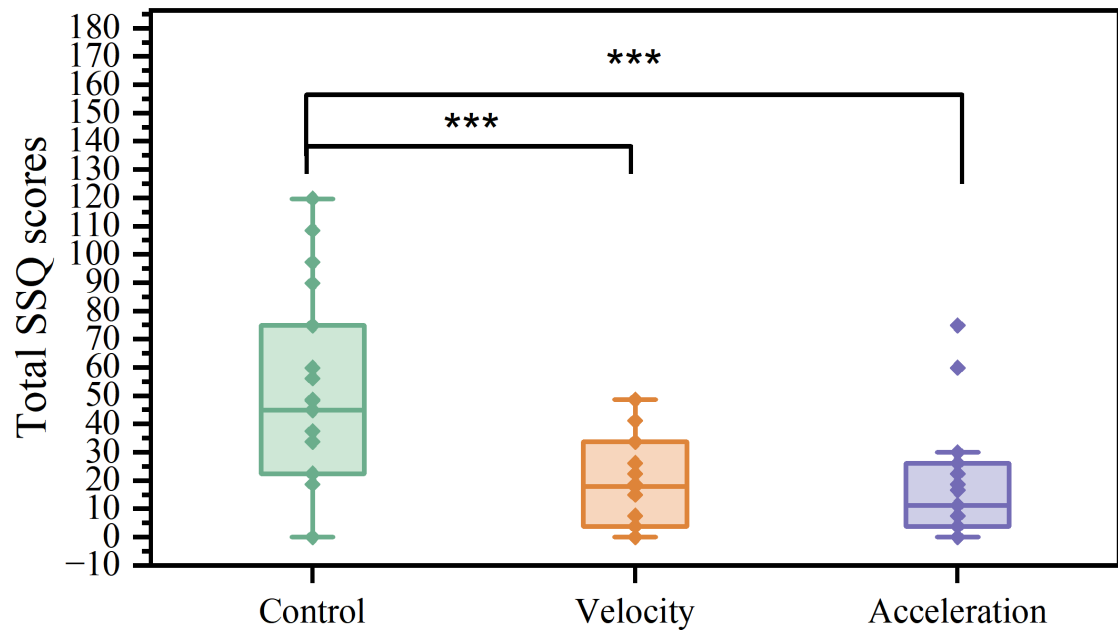


Figure 5.7: The total SSQ scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median. Lower SSQ scores indicate reduced levels of motion sickness.

comes, addressing **Sub RQ2.1** in **RQ2**.

Additionally, subjective ranking questions indicated that the acceleration-based cue resulted in lower user distraction. While previous studies have assessed the role of matched visual cues in alleviating motion sickness, the extent to which these cues might distract users has remained unexplored. However, since the initial intent was to compare the acceleration-based cue with common matched motion cues, the two conditions employed different backgrounds. The inconsistency of backgrounds used in the Acceleration and Velocity conditions could potentially confound the results. Therefore, in subsequent experiments, this limitation was addressed, and an additional condition to investigate the effects of gain to cues to see its effects on motion sickness and distraction was conducted.

5.3 Study 6 - Exploring Larger Acceleration Cue Coefficients

The results from Study 5 demonstrated the effectiveness of the acceleration-based design. However, this study compared the starfield acceleration cue to a common matched motion design

that used a cityscape instead of a starfield. As users exhibit different preferences and levels of distraction depending on the background design [121], it was necessary to ensure that the results were not attributable to differences in the stimuli and backdrops, which was addressed in Study 6. Additionally, We also tested this with acceleration cues for the first time, by including an additional condition in our study to investigate the effects of applying a 2x gain to the starfield displays to see its effects on motion sickness and distraction. Study 6 addressed **Sub RQ2.2**, **Sub RQ2.3** in **RQ2** and **RQ3**.

- **RQ2:** For linear motion, how is the trade-off between motion sickness and distraction impacted by visual cues that resolve sensory mismatch?
 - **Sub RQ2.2** How does the trade-off between motion sickness and distraction compare between existing velocity-based matched motion cues and acceleration-based cues?
 - **Sub RQ2.3** Can tuning the parameters of acceleration-based visual cues benefit user experience?
- **RQ3:** How to achieve minimally disruptive visual motion cues that balance motion sickness against distraction for Passenger VR?

5.3.1 Study Design and Setup

We adopted a within-subjects experimental design, with motion sickness levels, eye-tracking indexes, user distraction ratings, and task performance as dependent variables. Three experimental conditions were tested: *Acceleration*, *2X Acceleration*, and *Velocity*.

Acceleration Condition

The same virtual starfield display in Study 5 was developed, serving as the foundation for the visual cue design. This immersive dynamic scene, filled with virtual spheres resembling stars, used a particle system in Unity3D to generate the starfield. It spawned a constant stream of random red particles, which made the cues clearly visible against the black background, moving toward the camera object. This design subtly conveys the vehicle's motion through acceleration cues, potentially causing less distraction compared to traditional velocity-based matched motion designs.

2X Acceleration Condition

Perceptual manipulation in VR has a longstanding history [169], commonly employing translations gain to allow users to perceive larger virtual spaces within limited physical areas, thus expanding VR design capabilities and enhancing user experience [183]. Previous research on

visual cue gain or attenuation for matched motion designs has indicated that attenuation reduces distraction and enhances productivity, whereas increased gain has the risk of increases distraction [139]. Acceleration-based cues, compared to velocity-matched cues, have the potential advantage of reduced distraction. Therefore to explore whether applying gain to acceleration-based cues diminishes their distraction-minimizing benefits, we implemented a gain design for this condition. We used the same starfield design as the Acceleration Condition but doubled (2X) the particle movement speed to investigate its impact on mitigating motion sickness and distraction.

Velocity Condition

This condition utilized a matched motion design, where the backward movement velocity of the virtual starfield was consistent with the real-time vehicle velocity obtained from the vehicle's OBD interface. This approach follows standard matched motion design principles, replicating a passenger's actual visual experience of looking outside a moving vehicle at a 1:1 scale. Such designs have been extensively validated in simulators and real vehicles, effectively mitigating VR-induced motion sickness in transportation scenarios [19, 121, 142]. This design is widely recognized as the benchmark visual strategy for reducing motion sickness during in-vehicle VR use, thus providing a critical baseline for evaluating the effectiveness of our experimental conditions.

Matched-motion cues have consistently demonstrated effectiveness as the gold standard for mitigating motion sickness across various platforms—including both motion simulators [19, 38, 61, 83, 138, 143, 162] and real-world transportation [20, 122, 142, 159]. Moreover, previous studies have shown that the absence of visual cues frequently leads to severe motion sickness, causing participants discomfort and resulting in experimental interruptions. As a result, we adopted the matched motion (velocity-based) condition as our baseline rather than including a no-visual-cue control. Additionally, Study 5 has specifically validated acceleration cues as superior to no-cue conditions through real-world vehicle trials, further diminishing the necessity and ethical appropriateness of including a no-cue baseline.

By directly comparing our acceleration cue conditions against the matched-motion baseline, this design explicitly targets the critical issue of visual distraction. While matched-motion cues effectively alleviate motion sickness, their reliance on velocity-matched visual inputs inherently risks heightened visual distraction. Hence, our primary objective is to assess whether acceleration cues can comparably mitigate motion sickness while reducing visual distraction relative to this established standard.

5.3.2 Experimental Platform

The same model of Skoda Superb used in Study 5 was continued as the test vehicle. The rest of the setup remained consistent with Study 1. Participants sat in the rear-left seat, wore a Pico 4 Pro VR headset, watched videos, and answered related questions. There was a driver to control the vehicle and an experimenter to assist participants. For the Velocity condition, we used the PassengXR platform [111] to capture vehicle velocity. For other conditions, all the vehicle movement data was collected by a VR right-hand controller mounted in the car. The controller itself contains an IMU suitable for detecting acceleration.

5.3.3 Driving Route

The vehicle traversed the same 2-mile city road as in Study 5. Building upon the focus on linear motions in the first study, Study 2 introduced rotations including a 90-degree turn at both the start and end points of the route, as well as a 180-degree U-turn at the route's turnaround point, as depicted in Figure 5.5. These additions ensure we could test them for a prolonged period on the route without a break. As the vehicle turned, the visual cues also rotated in the same direction and angle to match the real car's movements, helping to minimize additional motion sickness caused by rotations. Figure 5.8 showcases the scene of the vehicle traveling on the experimental road during the experiment.

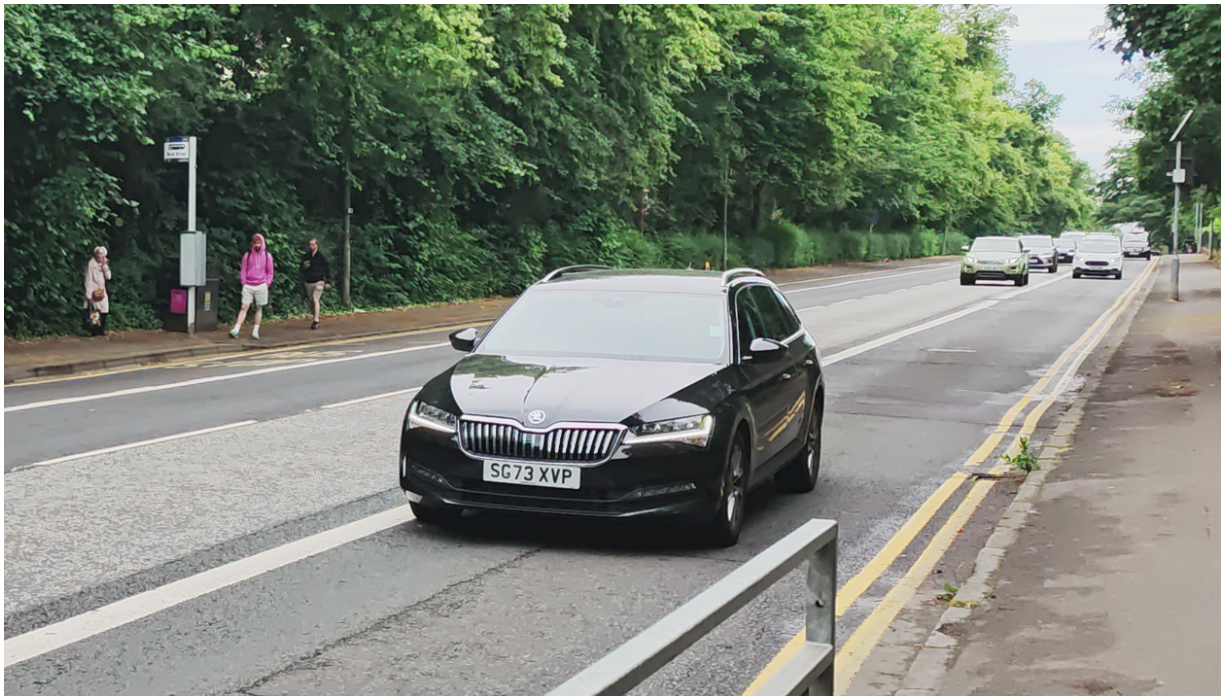


Figure 5.8: The experimental vehicle is travelling on the public road.

5.3.4 Measures

Motion Sickness

Participants completed the Simulator Sickness Questionnaire (SSQ) [78] before and after each condition, providing an overall measure of motion sickness. While immersed in the virtual environment and exposed to the physical motion, participants also continuously rate their motion sickness levels on the Misery Scale (MISC) [56] using a rating slider displayed beneath the VR task whenever they perceived changes in their motion sickness levels. If a participant's rating reached 7, indicating a feeling of mild nausea [56], the experiment was stopped to ensure the participant's safety and well-being. Participants were fully informed about these thresholds before the study began.

Video Task Performance

Participants viewed same six two-minute videos from the ActivityNet database [186] and answered four comprehension questions per video. Videos featuring minimal motion were selected to mitigate motion sickness. From an initial online test, four QA pairs per video were chosen based on achieving an ideal accuracy rate of 80%, ensuring the task was neither too challenging nor too simple.

For the experimental task in both studies, participants watched six two-minute videos from the ActivityNet database [186] and answered four questions per clip to assess comprehension. Videos were selected for minimal motion to prevent motion sickness, and four QA pairs per video were chosen based on a pre-test conducted on Prolific Prolific ($n = 100$ in total, for each video, $n = 20$). that ensured no prior knowledge was necessary and the difficulty was suitable. The task aimed to balance engagement and challenge by achieving an average accuracy rate of 80% in responses, which avoided overcomplexity and maintained participant interest.

Objective and Subjective Distraction

Distraction refers to factors interfering with an individual's ability to perform primary tasks and it can generally be categorized into three types: multitasking interference, external stimulus interference, and mind-wandering [163]. Based on this theoretical framework, this VR-based research involved a single-task paradigm in which participants' vision was restricted to the VR display without additional multimodal stimuli. Consequently, multitasking interference was minimized. Furthermore, since participants continuously viewed videos and responded to questions without breaks or relaxation intervals, mind-wandering was also substantially reduced. Thus, distraction predominantly arose from external visual stimulus interference.

To objectively quantify this distraction, we employed eye-tracking technology. Given that the primary task remained consistently centered within the visual field, with visual cues introduced peripherally, we developed an *Off-Target Index* to quantify visual distraction caused by

visual cues. Specifically, gaze points were continuously recorded throughout the experimental session. We defined the plane encompassing the primary task and the MISC slider as the target plane. Any gaze points recorded outside this target plane were categorized as distraction events. The total number of these off-target gaze points constituted the *Off-Target Index*, objectively reflecting visual distraction frequency. Additionally, the order of conditions and video content were counterbalanced to mitigate potential biases from participants' initial curiosity toward novel visual cues or differences in visual hotspots linked to specific videos.

Moreover, we implemented subjective measures to evaluate visual distraction. Participants completed a subjective ranking questionnaire at the experiment's conclusion, ranking distraction levels induced by visual cues across the three conditions from lowest to highest. Considering that forced linear rankings might inadequately capture participants' nuanced perceptions and attention as selective cognitive processes for stimulus and information processing, closely intertwined with distraction [22], we included an additional attention and focus rating questionnaire after each condition, where participants rated their perceived level of attention and focus on a slider scale ranging from 0 (low focus) to 10 (high focus).

5.3.5 Participants

Twenty-one participants took part in the study. Due to technical issues, one participant experienced interruptions in the transmission of vehicle velocity data via the OBD interface, and their data were subsequently excluded. Therefore, we collected 20 complete datasets, including 11 females and 9 males, with ages ranging from 22 to 28 years ($M = 23.95, SD = 1.82$).

5.3.6 Results

A single-factor Friedman's ANOVA was employed, followed by pairwise comparison tests with Bonferroni correction for *post hoc* comparisons among the different experimental conditions. Additionally, since Friedman's ANOVA cannot quantify evidence in favor of the null hypothesis when results are non-significant, Bayesian ANOVA was employed to assess whether there were meaningful differences across conditions and to quantify the strength of evidence supporting the absence of such differences [87].

Misery Scale Scores

To assess overall motion sickness symptoms, the averaged participants' MISC scores was used to reflect the overall discomfort level experienced. The results showed no significant differences among the conditions, $\chi^2(2) = 0.553, p = .759$. Across all conditions, participants' MISC scores were relatively mild (Acceleration condition: $M = 0.25, SD = 0.35$; 2X Acceleration condition: $M = 0.38, SD = 0.47$; Velocity condition: $M = 0.44, SD = 0.62$). To further evaluate the strength of evidence supporting the null hypothesis, a one-way Bayesian repeated-measures ANOVA was

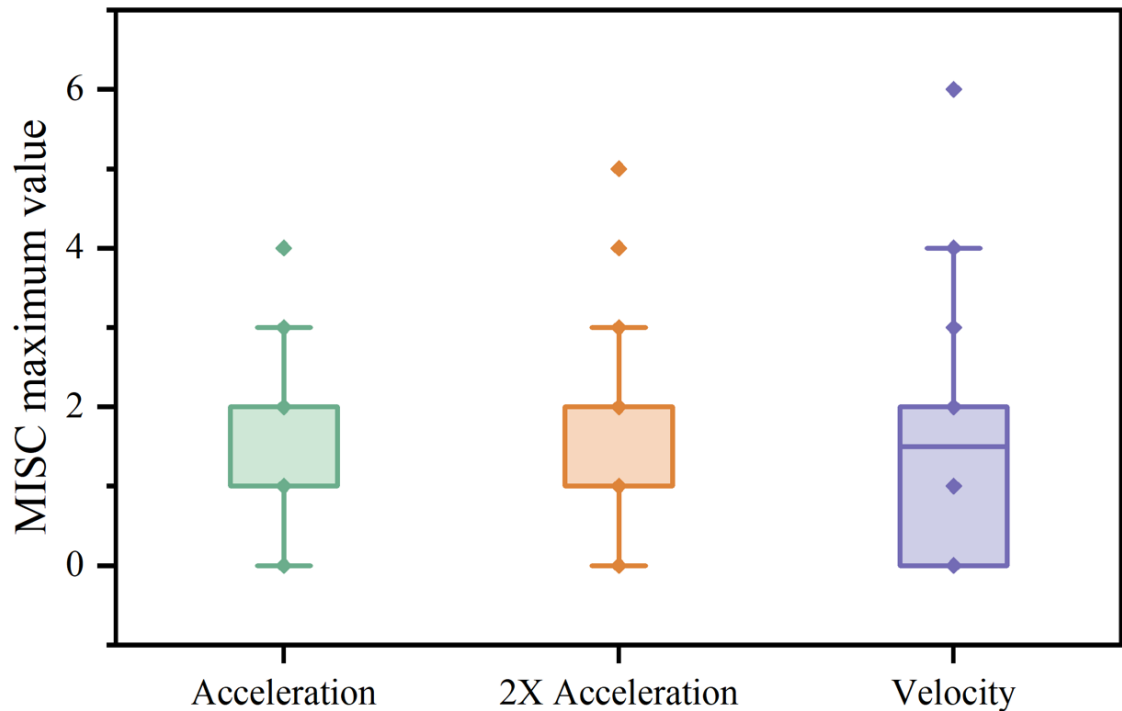


Figure 5.9: The MISC maximum value. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.

used. This analysis yielded a Bayes Factor of 0.185 in favor of the null hypothesis, indicating strong support under the Bayesian framework for the absence of significant differences among conditions. Specifically, the null hypothesis (no difference) is approximately 5.4 times ($1/0.185$) more likely than the alternative hypothesis, strongly suggesting no differences in average motion sickness levels across the three conditions.

In addition, the maximum MISC score selected by the user in each condition was used to reflect the peak discomfort level experienced. There were no significant differences between the conditions, $\chi^2(2) = 0.481, p = .786$, see Figure 5.9. Across all conditions, participants' maximum MISC scores were relatively mild (Acceleration condition: $M = 1.30, SD = 1.03$; 2X Acceleration condition: $M = 1.60, SD = 1.27$; Velocity condition: $M = 1.55, SD = 1.60$). A one-way Bayesian repeated-measures ANOVA was also used, which yielded a Bayes Factor of 0.062, indicating that the null hypothesis (no difference) is approximately 16 times ($1/0.062$) more likely than the alternative hypothesis. This strongly suggests that there were no differences in peak motion sickness levels among the three conditions.

Simulator Sickness Questionnaire

As all three sub-scales (Nausea, Oculomotor, Disorientation) yielded results similar to the total SSQ scores, only total scores are reported for brevity. There were no significant differences

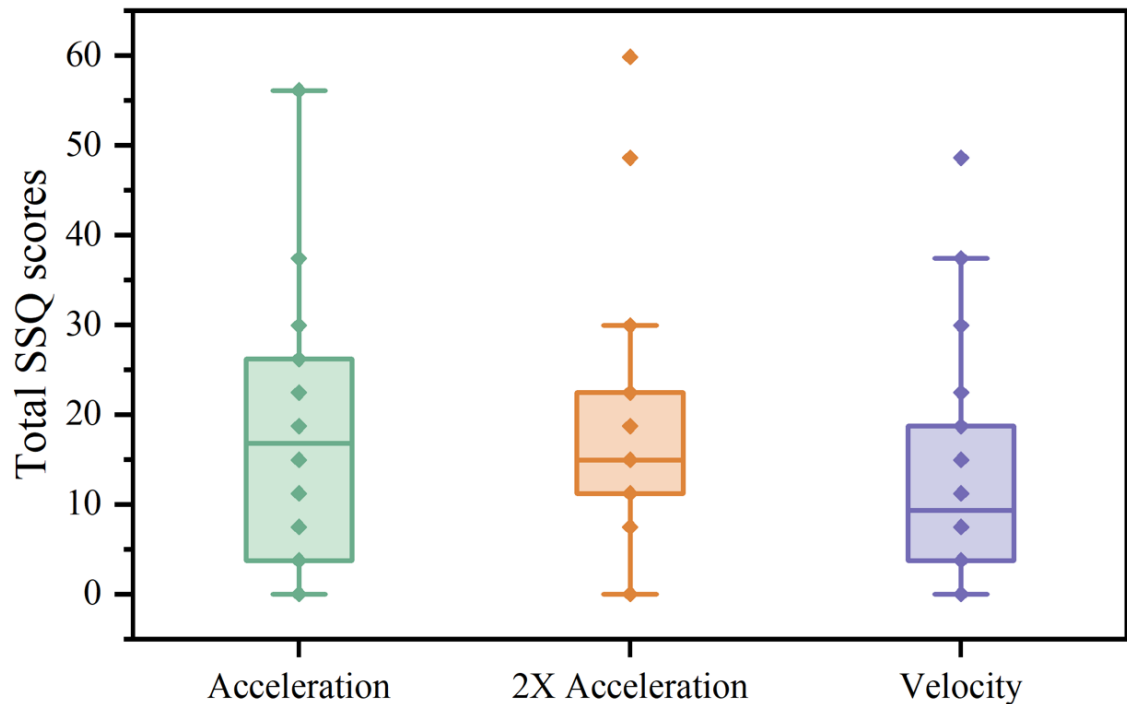


Figure 5.10: The total SSQ scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.

between the conditions, $\chi^2(2) = 5.312, p = .150$, see Figure 5.10. Across all conditions, participants' Total SSQ scores were relatively close (Acceleration condition: $M = 17.20, SD = 14.83$; 2X Acceleration condition: $M = 18.87, SD = 14.93$; Velocity condition: $M = 13.65, SD = 13.36$). A one-way Bayesian repeated-measures ANOVA was also used, which yielded a Bayes Factor of 0.075, indicating that the null hypothesis (no difference) is approximately 13 times ($1/0.075$) more likely than the alternative hypothesis. This suggests that there were no differences in SSQ scores among the three conditions.

Task Performance

Statistics on participants' accuracy in responding to the video task questions were compiled. These data serve as a reference for gauging participants' focus on the primary task. Task accuracy differed significantly between the conditions, $\chi^2(2) = 10.55, p = .005$, see Figure 5.11. *Post hoc* tests revealed a significantly higher level of accuracy in the Acceleration condition ($M = 76.9\%, SD = 0.06$) than the Velocity condition ($M = 68.7\%, SD = 0.73, p = .008$, Cohen's $d = 1.23$). No significant difference was found between the 2X Acceleration condition ($M = 71.3\%, SD = 0.08$) and Acceleration condition ($p = .246$). Also, no significant difference was found between the 2X Acceleration and Velocity conditions ($p = .618$).

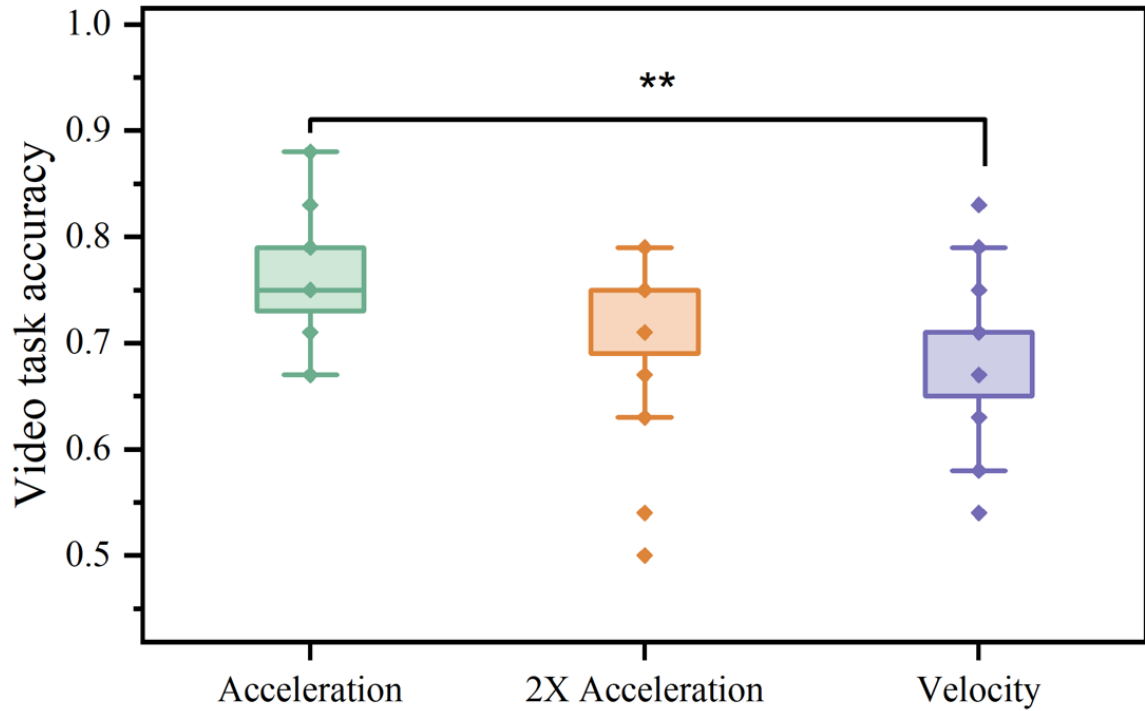


Figure 5.11: The video tasks accuracy rates. A higher accuracy rate indicates greater comprehension of the video contents.

Distraction and User Experience

For eye-tracking data, the gaze *Off-Target Index* described earlier was compared across three conditions. This index represents the cumulative count of gazes directed away from the task area during each condition. Higher values indicate that participants' gaze deviated more towards peripheral areas rather than the center. The results revealed a significant difference among conditions, $\chi^2(2) = 7.62, p = .022$. *Post hoc* tests revealed Acceleration condition ($M = 14.45, SD = 12.60$) had a significantly lower *Off-Target Index* compared to the Velocity condition ($M = 26.55, SD = 20.66, p = .043, \text{Cohen's } d = -0.707$). The Acceleration condition also approached significantly lower scores compared to the 2x Acceleration condition ($M = 27.45, SD = 20.87, p = .066$). No significant difference was observed between the Velocity and 2x Acceleration conditions ($p = 1.000$).

In the rankings of distraction levels, the rankings of three motion sickness mitigation designs were compared. A value of 1 was assigned to participant rankings indicating a higher level of distraction, 0 to a middle level of distraction, and -1 to rankings indicating a lower level of distraction. The final results differed significantly between the conditions, $\chi^2(2) = 16.30, p < .001$. *Post hoc* tests revealed both Acceleration ($M = -0.55, SD = 0.51, p = .000, \text{Cohen's } d = -2.13$) and 2X Acceleration conditions ($M = -0.15, SD = 0.75, p = .022, \text{Cohen's } d = -0.63$) had a significantly lower distraction level compared to the Velocity condition ($M = 0.70, SD = 0.66$).

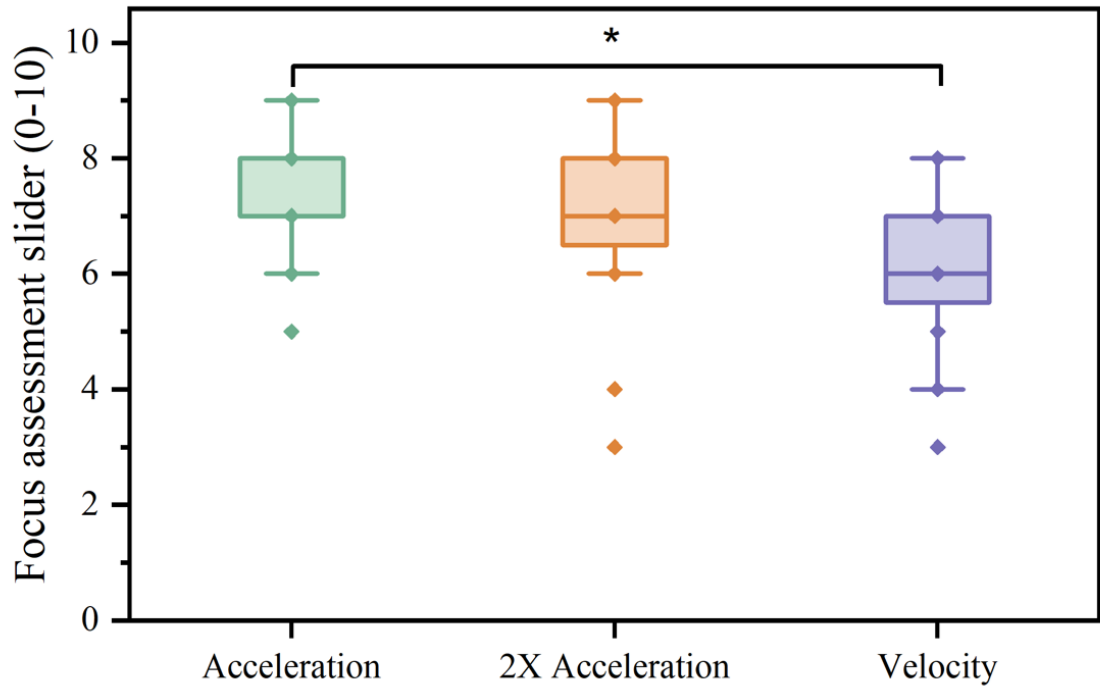


Figure 5.12: Participants' subjective focus ratings, with 0 representing extremely low focus and 10 representing extremely high focus.

There was no significant difference between the Acceleration and 2X Acceleration conditions ($p = .618$).

Significant differences were also observed in the focus assessment slider, $\chi^2(2) = 7.85, p = .020$. *Post hoc* tests revealed that Acceleration condition ($M = 7.45, SD = 1.10, p = .034$) had a significantly higher focus rating compared to the Velocity condition ($M = 6.10, SD = 1.25, p = .034$, Cohen's $d = 1.15$), see Figure 5.12. There was no significant difference between Acceleration and 2X Acceleration condition ($p = .912$).

5.3.7 Study 6 Discussion

The results of Study 6 once again demonstrated that acceleration-based cues perform as effectively in alleviating motion sickness as the commonly used matched motion cues, as evidenced by both the SSQ and MISC scores. This reaffirms the effectiveness of such design in mitigating motion sickness and positions acceleration visualization for linear motion as a promising approach for addressing motion sickness. In Study 6, since the same starfield design was employed, a better comparison of user distraction and immersion levels was possible through the results of the task accuracy rates. It is well established that higher levels of motion sickness tend to impair task performance [96, 138]. In this study, all conditions induced comparable levels of motion sickness, and task difficulty was controlled across trials. As the only manipu-

lated factor was the type of visual cue, the observed reduction in task accuracy can be attributed to the additional distraction introduced by the velocity cues, rather than differences in motion sickness. Based on this comparison, it was confirmed that acceleration-based cues cause less distraction than velocity-based cues, thereby enhancing the VR experience and addressing **Sub RQ2.2**. Regarding **Sub RQ2.3**, it was observed that both the Acceleration condition and the 2X Acceleration condition maintained similar levels of motion sickness mitigation, indicating that increasing the gain of acceleration cues does not result in higher MISC or SSQ scores. Additionally, the results for subject distraction levels indicated that the 2X Acceleration did not result in significantly higher levels of distraction. However, objective assessment using the *Off-Target Index* revealed a significant increase in users looking outside the task, reaching levels comparable to those observed with acceleration cues.

5.4 Limitations

5.4.1 Route and Driving Conditions

The driving route in this study was primarily linear, enabling effective isolation and focusing on linear motion effects. However, this also implies that findings primarily contribute to the understanding of motion sickness induced by linear movements. Nevertheless, these initial findings provide a foundation for future studies. Further studies should be undertaken in different driving environments, for example motorways, to look at the effectiveness of cues in more driving scenarios.

5.4.2 Driving Conditions

Vehicle velocity was regulated to 30 mph in compliance with speed limits and ethical guidelines, which restricted the duration of acceleration and deceleration phases as well as the driving profile overall. This could have contributed to the relatively low levels of motion sickness observed. Furthermore, despite efforts to schedule the experiment during off-peak traffic hours, variations in traffic conditions inevitably affected the number of accelerations and decelerations encountered by participants, resulting in inconsistent, but realistic, experimental conditions across sessions. This meant a lack of control in the experiments but at a large gain for ecological validity.

5.4.3 Tasks

Watching videos is a very common activity, but future studies should look at a wider selection of tasks to see how acceleration cues perform in a different context. Additionally, unlike motion sickness, no gold-standard measurement exists for assessing user distraction. We utilized a variety of methods, including task performance assessments and subjective rankings. However,

the results derived from these diverse methods may not be entirely consistent. In future studies, we will incorporate other metrics and interviews to get more insight on user distraction.

5.4.4 Distraction Measurement

The action of sliding the MISC slider itself can distract users, as they need to divert attention from the task to assess their current level of motion sickness and ensure the slider is moved to the correct position. This is an inherent drawback of real-time sliders. An alternative could be fixed-interval, non-real-time assessments of motion sickness, though this method lacks sensitivity and may miss changes in motion sickness that occur between assessments.

Furthermore, regarding the video task content, although the video selections were pre-screened to prevent visually induced motion sickness, the content of the tasks themselves might still impact the users' focus. Although video tasks provide a more realistic simulation of users' VR experiences compared to mathematical tasks, they have shortcomings compared to the previous mathematical tasks used.

Unlike motion sickness, there is no established gold-standard metric for evaluating user distraction. This study employed multiple assessment methods, which may have introduced inconsistencies. Future studies should integrate additional quantitative metrics and qualitative interviews to gain deeper insights into user distraction.

5.4.5 Lack of a Baseline Condition on Motion Sickness

As Study 5, we did not include a no-visual-cue condition as the baseline for motion sickness in Study 6, considering both ethical concerns for participants and the primary focus of this study. The results show that acceleration cues perform similarly to conventional matched cues in mitigating motion sickness, aligning with previous findings. Future studies that include a baseline condition for motion sickness would allow for a more comprehensive evaluation of the effectiveness and contribution of visual cues in motion sickness mitigation.

5.5 General Discussion

This chapter, conducted in a real-road traffic environment, demonstrates for the first time that visual cues based on acceleration are as effective as commonly used velocity-based matched motion cues in mitigating motion sickness for passengers in linear motion. Additionally, these acceleration-based cues reduced the distraction associated with visual cues, offering a viable alternative to matched motion designs for a range of passenger VR applications like productivity, entertainment or well-being apps.

5.5.1 The Similar Effects of Acceleration and Velocity Cues on Motion Sickness

Studies in this chapter employed both MISC and SSQ to evaluate motion sickness levels. The results from Study 5, when compared to a control condition lacking visual cues, confirmed the effectiveness of acceleration cues in reducing motion sickness. Furthermore, when these acceleration cues were compared with two different designs of velocity cues (city scape, starfield), no significant differences were observed in either MISC or SSQ scores. Bayesian analysis further strongly indicated equivalence between the designs, with results remaining closely aligned. Consequently, acceleration-based designs have proven to be effective in mitigating motion sickness, thereby providing a clear answer to **RQ2.1**. This indicates that, in addition to displaying visuals that align with expected views in VR, directly matching the perceived self-motion of the vestibular system is a viable strategy.

Although it may seem counter intuitive, acceleration cues move backwards in the visual field during vehicle deceleration, despite the vehicle still moving forward, which is typically viewed as a visual conflict potentially leading to motion sickness. Results demonstrate that properly matching the perceived motion of the vestibular organs performs comparably to traditional matched motion. This approach could have wide application as such starfield like cues could be integrated into most types of VR environment and such design obviates the need for additional hardware to acquire vehicle velocity and still delivers comparable outcomes, thus lowering the barriers to implementation in other forms of transport and in future autonomous vehicles. This discovery heralds a new frontier in the design of visual cues for passenger VR, and opens the door to designing *minimally disruptive spatial motion cues* based on acceleration for AR/XR generally.

5.5.2 Velocity-based Cues Introduce Greater Distraction and Reduced Focus Compared with Acceleration-based Cues

Visual motion sickness mitigation cues inevitably introduce some distraction. However, in the context of using VR in vehicles, mitigating motion sickness remains essential. Thus, it is crucial to strike a balance between reducing motion sickness and minimizing the distractions caused by visual cues. In terms of task performance, no significant differences were observed in Study 5. However, Study 6 revealed a significant decrease in accuracy under the Velocity condition compared to the Acceleration condition. Our tasks mimic common VR activities such as video viewing, suggesting broader implications for VR interaction design. It is well established that higher levels of motion sickness tend to impair task performance [96, 138]. In Study 6, all conditions induced comparable levels of motion sickness, and task difficulty was controlled across trials. As the only manipulated factor was the type of visual cue, the observed reduction in task accuracy can be attributed to the additional distraction introduced by the velocity cues,

rather than differences in motion sickness. This answers **RQ2.2**.

In both studies, participants also rated velocity cues as significantly more distracting than acceleration cues. This suggests that, with careful design, we can reduce distraction while maintaining good motion sickness mitigation performance.

In Study 5, the Velocity condition was designed using a typical urban background, while a starfield background was introduced for the velocity-based cue. This difference in backgrounds potentially explained the absence of significant differences in task accuracy observed in Study 5. When employing the same types of cues (acceleration/velocity), the starfield design, being less common than everyday cityscape scenes, could be more captivating to users. However, Study 5 utilized different types of motion cues—acceleration in the starfield and velocity in the cityscape. The disparity between the acceleration cue and velocity cue significantly impacted distraction more than the background design, a finding also demonstrated in Study 6. Therefore, our starfield acceleration cues could benefit from further refinement, such as reducing the density of the starfield or substituting it with other elements to further minimize distractions. Overall, our findings suggest that various visual cues can indeed introduce additional distractions, subsequently impacting user experience and efficiency in VR environments.

5.5.3 No Evidenced Benefits of Gain for Acceleration Cue Design

It was observed several intriguing results regarding newly introduced 2x acceleration cues. Therefore, the conclusion for **RQ2.3** remains inconclusive. The results can be interpreted from two perspectives. In terms of motion sickness, gain could be applied to acceleration cues without negatively impacting motion sickness mitigation. These observations align with prior findings involving velocity-based matched motion cues [139], which also showed the feasibility of applying visual gain without adverse effects. Such results have substantial implications for the broader applicability of our designs. XR designers are not limited to a single visual cue speed, but can instead match cue gains to specific VR tasks or games. For instance, designers could employ gain-enhanced acceleration cues in interstellar travel games [139]. Further research should investigate the possibility of attenuation, with even less cue movement there could be lower distraction, if the effects on motion sickness mitigation are maintained.

Regarding distraction, the results were less consistent. Subjectively, participants reported no noticeable change in focus after the gain was applied. We believe this is because our design intentionally avoids introducing distracting visual cues during steady-speed periods. During such periods, cues remain static regardless of gain adjustments. As vehicles often travel at constant speeds (e.g., on highways), participants' subjective experiences remain largely unaffected. However, objective assessment using the *Off-Target Index* revealed a significant increase in users looking outside the task. We attribute this to the gain-enhanced visual cues during acceleration, which likely amplified the perceived motion and thus impacted the distraction measures.

Chapter 6

Conclusion

6.1 Introduction

This thesis explored the balance between alleviating motion sickness and user distraction when using VR visual cues in vehicles. The thesis statement was as follows:

This thesis investigates how innovative visual cues within VR environments can effectively mitigate motion sickness while minimizing distraction during NDRTs when passengers are in motion. Current approaches, such as *matched-motion* cues, reduce motion sickness but introduce significant visual distraction, detracting from the overall passenger experience. To address this challenge, this research explores novel *minimally-disruptive motion cues* tailored specifically to linear and rotational vehicle motions, integrating subtle yet effective motion representations into VR scenes. By comparing these designs against existing methods through real-road studies, the thesis identifies visual cue strategies that optimally balance the reduction of motion sickness with minimal interference to user attention, and provides practical design principles to deepen theoretical understanding, supporting the broader adoption of VR in transportation contexts.

In the experimental chapters, six studies are presented that support this statement and seek to answer the thesis research questions. Initially focusing on rotational motion, Chapters 3 and 4 explore different types of novel visual cues to reduce motion sickness. Chapter 3 begins with implicit cues, designing ways to convey motion cues through manipulating the orientation of planar content, without any additions to the content itself. Two lab studies validate this design and the results prove that the design mitigates motion sickness by providing awareness of physical orientation changes through changes in the visual orientation of the virtual planar content. Chapter 4 starts from physical motion within VR to introduce physics-based motion sickness mitigation cues. One study is used to prove the design's effectiveness in alleviating motion sickness, and another study compares it with common solutions, assessing the distraction

caused by these three visual cues. The designs in this thesis reduced motion sickness and were less distracting than existing solutions, showing it is possible to control motion sickness without user distraction.

Subsequent research is based on linear motion. Chapter 5 presents a novel approach to mitigating motion sickness through acceleration-based cues that convey information about linear vehicle motion. Two studies were conducted in a real driving scenario. The results showed that both acceleration cues and standard velocity cues significantly mitigated the symptoms of motion sickness. Furthermore, when comparing distraction levels, the acceleration cue effectively reduced motion sickness and also caused less user distraction compared to other designs. In this chapter, these findings are used to answer the Research Questions and summarize the Contributions. Furthermore, the limitations of this thesis will be discussed, followed by a description of future work.

6.2 Research Questions

6.2.1 Research Question 1

- **RQ1:** For rotational motion, how is the trade-off between motion sickness and distraction impacted by visual cues that resolve sensory mismatch?
 - **RQ1.1** What are the effects of using implicit cues that manipulate the movements of 2D planar virtual interfaces?

Two studies, detailed in Chapter 3, were conducted to investigate this question. Since distraction is considered a factor that disrupts an individual's ability to concentrate on the primary task, the initial approach focused on minimizing these factors. Study 1 explored implicit cues by manipulating the movement of existing virtual interfaces showing content to the user. The motion of these interfaces allowed for the transmission of motion information without introducing additional visual elements or affecting the content in any way. Study 1 gave five minutes of motion sickness stimulation using a rotating chair and compared the performance of visual cues under different parameter settings with a control condition in terms of alleviating motion sickness. Following the conclusion that this design effectively alleviated motion sickness, Study 2 further investigated the optimal parameter settings identified in Study 1. It involved longer stimulation times and larger rest intervals to compare motion sickness measurement indicators and task measurement indicators directly. Results based on the SSQ questionnaire and MISC slider scores both indicated that implicit cues had a significant effect on reducing motion sickness-related symptoms and could be less visually distracting than existing cues.

For **RQ1.1**, implicit cues proved effective in mitigating motion sickness. Under testing with a rotational motion simulator, this design significantly reduced subjective motion sickness symptoms. This alleviation occurs not only in users' self-assessments after the stimulus ends but also

in real-time assessments during the experiment. Regarding the trade-off between motion sickness mitigation and distraction caused by visual cues, this design introduced no additional visual elements or occupied space within the VR environment. As a result, it avoided introducing factors that could disrupt an individual's focus on primary tasks. Since no external visual cues were added around the task area, where human vision tends to be particularly sensitive, this approach reduced distraction compared to methods requiring extra visual components. Therefore, for rotational motion, implicit cues can effectively address the mitigation of motion sickness and minimize distraction caused by visual cues. Such cues reduce motion sickness without the need for moving environments or additional virtual elements. However, in certain scenarios, users may require a fixed NDRT interface, or moving the visual display could interfere with the NDRT task being performed. As a result, this prompted the exploration of alternative visual cues that leave the virtual display untouched. This consideration led to the development of a second design approach.

- **RQ1.2** What are the effects of using explicit physics-based cues presenting virtual objects that react to the forces experienced by the vehicle?

Two further studies, described in Chapter 4, were conducted to explore the efficacy of a novel type of visual cue based on physical motion of objects within the scene: in this case, hanging balls. These cues were inspired by the movement of objects in the real world under the influence of external forces. Study 3 demonstrated the effectiveness of the cues. Study 4 investigated the impact of these physics-based cues compared to two other distinct cue types (direction, and speed-and-direction cues) on mitigating motion sickness and their level of user distraction. The results showed that both physics-based cues and speed-and-direction cues significantly mitigated the occurrence of motion sickness. Furthermore, when comparing the distraction levels of the three visual cues, the speed-and-direction based cue caused the highest level of distraction. Our physics-based cue reduced motion sickness but without being as distracting, suggesting they are an effective solution to both problems.

For **RQ1.2**, when employing cues such as presenting virtual objects that react to external forces, these cues can also mitigate motion sickness. This conclusion has been validated through multiple studies and various measurement methods. Unlike the implicit cues in Chapter 3, explicit physics-based cues and speed-and-direction cues necessitate additional UI elements beyond the task at hand. Therefore, the introduction of these cues inevitably introduces extra distractions. However, the novel technique presented achieves a balance between mitigating motion sickness and reducing distraction. Consequently, for rotational movements, the careful design of explicit cues, such as the physics-based cues proposed in this thesis rather than directly matching external vehicle motion, can both alleviate motion sickness and reduce user distraction.

In summary, for **RQ1**, concerning rotational motion, this thesis identifies the inadequacies in the common solution of speed-and-direction cues regarding user distraction and introduces

two alternatives that achieve a better balance: implicit cues and physical based cues. Through four studies, the effectiveness of these proposed solutions in alleviating motion sickness was first demonstrated, followed by their ability to cause reduced user distraction. Consequently, for rotational motion, designs can replace the typical matched-motion cues to achieve a more favourable trade-off. These designs may involve using the VR task's inherent motion or the physical movement of objects within the VR environment. These findings enhance the overall user experience. Following these insights, the integration of VR devices into moving platforms such as simulators and vehicles becomes more practical.

6.2.2 Research Question 2

- **RQ2:** For linear motion, how is the trade-off between motion sickness and distraction impacted by visual cues resolving sensory mismatch?
 - **RQ2.1** Can acceleration-based visual cues reduce motion sickness?

Based on the principles of how the vestibular system perceives motion, Study 5 employed acceleration cues using starfield elements for motion sickness mitigation. The study compared acceleration cues, existing velocity-based cues, and a control condition (no cue) over a 12-minute road trial, evaluating their effects on motion sickness mitigation and distraction levels. The results, based on the SSQ Questionnaire and MISC scores, indicated that the acceleration-based cue significantly reduced motion sickness compared to the Control condition. This confirmed the effectiveness of presenting acceleration cues for alleviating motion sickness. Therefore, for **RQ2.1**, the thesis confirms that visual cues for acceleration, designed based on the principles of motion perception of the vestibular system, are effective. These findings initiate a discussion on which cues are necessary for mitigating linear motion sickness. The novel acceleration cues can achieve results comparable to those of velocity cues in alleviating motion sickness.

- **RQ2.2** How does the trade-off between motion sickness and distraction compare between existing velocity-based matched-motion cues and acceleration-based cues?

Studies 5 and 6 addressed this question. Study 5 compared the performance of velocity-based cues with matched-motion cues set against common urban scenes used as VR backgrounds in alleviating motion sickness. It also contrasted the degree of user distraction between velocity-based cues and matched-motion cues. Both studies utilized real vehicles as experimental platforms to enhance ecological validity. The results from Study 5 indicated that velocity-based cues not only mitigate motion sickness effectively, similar to existing matched-motion cues, but also exhibit lower subjective distraction ratings. In Study 6, employing the same starfield background design between conditions allowed for a better comparison of user distraction. This confirmed that acceleration-based cues cause less distraction than matched-motion cues. Thus, for **RQ2.2**,

this thesis presents a novel approach to mitigating motion sickness through acceleration-based cues that convey information about linear vehicle motion.

The results demonstrated for the first time that velocity-matched cues are not necessary. Novel acceleration cues can achieve results comparable to velocity cues. This design offers significant advantages in terms of hardware complexity and also reduces user distraction. It emphasizes the importance of minimally distracting cues to enhance the overall user experience. This design effectively achieves the balance stipulated in **RQ2**.

- **RQ2.3** Can tuning the parameters of acceleration-based visual cues benefit user experience?

In Study 6, the parameters of the acceleration-based visual cues were adjusted to explore whether different settings could impact performance. A 2x gain was applied to the motion of the visual acceleration cues. Results indicated that the higher gain did not produce significant differences in motion sickness mitigation compared to the 1x condition. Regarding distraction, participants reported no noticeable change in focus after the gain was applied. However, objective assessment using the *Off-Target Index* revealed a significant increase in users looking outside the task. Consequently, for **RQ2.3**, there is no evidence supporting the benefits of a 2x gain in acceleration cue design. However, this level of gain also did not lead to a further worsening of motion sickness symptoms. This suggests that both moderate gain (and potentially attenuation) can be applied to acceleration cues without negatively impacting motion sickness mitigation.

This finding holds significant implications for the broader application of such designs. Acceleration-based visual cues can be adapted for various purposes within VR development. For example, gain-enhanced acceleration cues could be utilized in scenarios like interstellar travel games, where distraction is less critical, to enhance the sense of motion. Conversely, attenuated cues would be more suitable for contexts requiring higher user focus, such as productivity tasks or reading, where minimizing distraction is essential. However, only a 2x condition was tested. Although based on similar studies [139], the results could apply to reasonable gains and potentially attenuation, the outcomes for more extreme gains might differ due to a ceiling effect.

6.2.3 Research Question 3

- **RQ3**: How to achieve minimally disruptive visual motion cues that balance motion sickness against distraction for Passenger VR?

For **RQ3**, all six studies presented in this thesis contribute to addressing this question. These studies first identified feasible designs for minimally disruptive visual motion cues that balance motion sickness mitigation and distraction in passenger VR, based on existing research. In

addition, the following section on *Future Applications* proposes potential directions that further contribute to this topic, collectively providing a comprehensive response to **RQ3**.

For rotational motion, this thesis proposes two approaches: one implicit method that conveys motion information through the rotation of the NDRT content itself, and another utilizing physics-based cues. The former offers an effective solution for scenarios centered around a single 2D NDRT interface, leveraging the interface’s own rotation to mitigate motion sickness without introducing additional cues. The latter, while occupying limited VR background space, is less disruptive than conventional matched-motion designs, making it suitable for a wider range of applications. Table 6.1 presents a multi-dimensional comparison between the techniques proposed in this thesis and conventional matched-motion cues for rotational movements.

Comparison Dimension	Implicit Cues	Physics-based Cues	Matched-motion Cues
Visual Field Occupancy	No needed	Uses partial NDRTs background	Full NDRTs background
Visual Element Composition	No additional elements required	Blended into background	Requires additional elements
Effectiveness in reducing motion sickness	Effective	Effective	Effective
Level of Distraction	Lower distraction	Lower distraction	Cause distraction
Generalizability	Suitable for 2D NDRTs only	Suitable for most cases	Suitable for most cases
Drawbacks	Limited use cases	Dependent on existing VR elements	Distraction, large visual occupancy

Table 6.1: Comparison of Three Visual Cue Designs

For linear motion, this thesis introduces acceleration-based cues as a viable solution to address both motion sickness and distraction challenges. These cues enable more streamlined, abstract, and implicit designs that move beyond the constraints of matched-motion approaches, offering greater flexibility and enhancing the overall user experience. Additionally, this design reduces hardware complexity by eliminating the need for external motion data, positioning it as a key component in future VR interactions within vehicles.

Looking ahead, combining multiple types of cues holds great potential for future passenger VR design. Integrating both rotational and linear cues can better accommodate real-world driving scenarios, enabling the creation of visual motion cues that effectively balance motion sickness mitigation with minimal distraction.

6.3 Future Applications

6.3.1 Low-Distraction / Minimally Disruptive Visual Cues in Future Passenger VR Applications

This thesis has demonstrated that various visual cues used within VR cause low distraction and effectively mitigate motion sickness. These designs could be highly beneficial if integrated into different types of in-vehicle applications, such as productivity-oriented applications within in-car VR systems. In scenarios that demand focus, the introduction of low-distraction cues, or even hiding the cues, could support greater focus on the primary NDRT. Based on the research on gain coefficients in Study 6, future studies might also explore attenuation. Similarly, future research could introduce a threshold for visual cue movement, where static or hidden cues might be displayed when acceleration values are low, as motion sickness is less likely to occur under these conditions. Furthermore, the application of visual cues can be both dynamic and personalized, enabling users to select different mitigation modes tailored to their preferences. VR applications could optimize user experience by dynamically switching between these modes, contingent upon the user's detected motion sickness status [98].

6.3.2 Using Extended/Mixed/Augmented Reality Devices to Deliver Generalised Spatial Motion Cues

To eliminate external distractions within environments, the studies in this thesis employed VR devices capable of entirely obscuring external surroundings to validate the designs. In contrast, XR devices such as AR glasses [167] allow users in vehicles, airplanes, or trains to remain aware of their physical surroundings while engaging in virtual activities, such as reading a physical book, to browsing the web on a virtual display. In such scenarios, the ambient visual information transmitted through XR devices can help alleviate motion sickness. However, matched-motion cues that require additional background elements may obstruct this surrounding view, becoming a drawback. Most visual cue designs in this thesis require minimal display space and feature an all-in-one configuration, making them ideally suited for deployment on XR devices that are worn all day. The implicit cues only require the motion of the NDRT content itself, aligning well with XR applications where 2D virtual elements are common. Similarly, physics-based and acceleration-based cues do not occupy extensive background space, unlike traditional matched-motion cues. As long as there is minimal space on the XR display interface, these cues can be effectively rendered, offering a lightweight and non-intrusive solution. This enables continuous motion sickness mitigation for passengers, addressing one of the major challenges facing XR adoption in everyday use.

6.3.3 Towards Novel Multimodal Motion Cue Designs

The effectiveness of implicit/acceleration/physical cues liberates us from the constraints of conventional matched-motion cues, allowing for further progress towards more novel multimodal motion cue designs. Future designs could integrate these cues into the movement of more VR scene elements, such as cityscapes, clouds, snow, and rain, to synchronize with real environmental/auditory cues and maintain immersion in VR devices. For example, snowflakes in a winter scene in a game could move based on the vehicle's acceleration; chandeliers in a VR theatre could sway to convey rotational motion information. Additionally, exploration into additional multimodal cues is warranted, where acceleration information is paired with acceleration-based auditory cues. For instance, the sounds of accelerating engines or decelerating brakes could enhance the perception of motion. The research discussed in this thesis enables more flexible design of multimodal cues to achieve a superior user experience.

6.4 Contributions and Recommendations

6.4.1 Thesis Contributions

This thesis contributes novel insights into the fields of VR vehicular experiences and motion sickness. The work in the thesis:

1. Developed several novel visual motion cues for VR that reduce motion sickness and minimize user distraction, while achieving similar efficacy to traditional matched-motion cues. These cues have been validated through tests conducted both in laboratory settings or real-world vehicles, covering common types of vehicular motion. This work advances the application of VR and XR technologies in transportation contexts.
2. Demonstrated through multiple studies that existing matched-motion cues cause user distraction and emphasized the importance of balancing motion sickness mitigation with the reduction of distractions by defining and demonstrating the need for minimally-disruptive motion cues. Based on research into user distraction, visual cues were designed to maintain the effectiveness of matched-motion cues while significantly lowering distraction levels. Additionally, this work offers novel insights into how these innovative cues can shape the future development of visual and multimodal motion cueing strategies.
3. Simplified visual cue integration in virtual reality, enabling effective motion cues to be delivered based on controller IMU data alone, rather than relying on velocity data or external platform-provided data [111]. This significantly reduces the time, cost and complexity of using visual motion cues;

6.4.2 Design Recommendations

This thesis established effective strategies for designing low-disruptive visual motion cues in Passenger VR. Based on the findings, the following design recommendations are proposed to enhance user experience and the experimental design approach in human-computer interaction experiments:

1. The design and deployment of visual cues can be made more flexible, without being strictly constrained to 100% motion-matched cues or requiring their constant presence throughout the entire experience.

First, by focusing on the principle of conveying motion information, the design of visual cues can adapt to the needs of various VR scenarios in different ways. The physics-based and acceleration-based cues proposed in this thesis show that low-optic-flow designs can achieve effects comparable to fully matched cues while reducing distraction. This expands the freedom of design and allows motion cues to be integrated in a less intrusive manner in contexts where matched cues may be disruptive. For example, in virtual theater or virtual workspace environments, matched cues may break immersion. Motion cues can instead be conveyed through physical principles, such as the swaying of lights or hanging objects, to deliver motion information more appropriately. This approach frees designers from the constraints of traditional matched cues and supports the development of more innovative designs.

Second, the application of matched cues can be more flexible. As matched cues are effective in reducing motion sickness, they are especially recommended for more susceptible users. In balancing mitigation and distraction, it is important to prioritize user comfort to prevent resistance to VR due to severe motion sickness. For other users, matched cues can be deployed selectively. For instance, acceleration-based cues are less distracting partly because they remain static during steady-speed travel. In scenarios such as highway driving, where speed is high and changes are minimal, acceleration-based cues or the omission of matched cues may be preferable.

2. For within-subject experiments on motion sickness, longer intervals between conditions are recommended. In the studies presented in this paper, intervals longer than 24 hours were used to avoid the cumulative effects of motion sickness. Compared to the short intervals used in Study 1, participant feedback suggests that this longer interval design helps reduce the impact of motion sickness from the previous session on the next. Even when experimental conditions do not allow for such long intervals, the experimenter should ensure sufficient rest for participants and assess this through various methods, such as using the SSQ.
3. Multiple motion sickness assessment methods are necessary for motion sickness exper-

iments. Real-time assessment tools, such as sliders, may be overlooked by participants during the experiment, while post-experiment assessments, such as the SSQ questionnaire, may lead to participants forgetting certain sensations experienced during the experiment. Researchers should employ a combination of methods to assess motion sickness accurately.

4. For VR tasks, it is important to consider how participants' cultural and academic backgrounds may influence their task performance. For example, a participant who is not proficient in mathematics may experience a performance bottleneck due to their own mathematical abilities, rather than the experimental conditions, across multiple experimental sessions. Some studies in this thesis employed math-based tasks, as participants were primarily school-aged individuals from various linguistic backgrounds who had received basic mathematical education. However, due to variability in English reading proficiency, math problems were selected to minimize language dependency. Given that the math tasks were designed to be simple, participant performance was not affected in this study. Nevertheless, this remains an important consideration for future research using similar task types.

Similar issues may arise in tasks involving reading or watching videos. Researchers can tailor the selection of appropriate tasks based on the experimental context and the characteristics of the target population involved. This thesis recommends avoiding tasks that require intensive mathematical computation when working with participants with diverse educational backgrounds. Likewise, when participants include non-native speakers, tasks involving heavy reading or verbal responses should be minimized. These strategies can help reduce the confounding influence of participant backgrounds on experimental outcomes.

5. When conducting motion sickness experiments in real vehicles, researchers should be mindful of how vehicle settings may impact motion sickness. Ideally, conditions such as cabin smell, temperature, window open/closed status, and other environmental factors should be kept consistent across groups to maintain control over variables and avoid introducing confounding factors that could affect the experimental results.
6. When researchers use different car brands for speed-related experiments, they should be aware that even with the same OBD protocol, some brands, such as Nissan, may modify the protocol, leading to compatibility issues in data reading. Similar problems can also occur with certain electric vehicles.

6.5 Limitations

6.5.1 The Integration of Multiple Cues

This thesis conducted separate studies on the rotational and linear motions of vehicles, as distinguishing between different types of visual cues allows for better control of variables during experimentation. However, vehicle motion on roads often involves a combination of both types. For instance, a vehicle turning might simultaneously involve both rotation and deceleration, necessitating the integration of multiple cues in certain scenarios. Due to time constraints, further experiments exploring combinations of different types of visual cues were not conducted. For example, the implicit cues introduced in Chapter 3 are based solely on the NDRT interface, while the acceleration-based cues in Chapter 5 rely on the VR background. Since these two types of cues are implemented in separate visual layers, they do not conflict in terms of display technology. Their integration is a promising direction for future research, as it may lead to more effective solutions for in-vehicle VR applications and improve the adaptability of such systems. In addition, applying single types of cues to different types of motion also warrants investigation. For instance, the implicit cues discussed in Chapter 3, originally designed for rotational motion, could be adapted to linear motion by shifting the movement of interface elements from left–right to forward–backward. Similarly, the physical cues described in Chapter 4 could be modified to swing forward and backward, rather than side to side, to better match linear motion patterns.

6.5.2 Classification of Vehicle Motion

In this thesis, the primary motions of vehicles are simulated as linear and rotational movements, which are the most common types of vehicle motion. However, vehicles may also experience other motion stimuli such as pitching and rolling. Although these motions may not be as prevalent as those discussed in this thesis, they can still contribute to the accumulation of motion sickness. The use of visual cues to mitigate motion sickness for these types of movements remains a topic worthy of study. On the other hand, the development of future vehicle suspension systems may reduce this limitation. Vehicle motions are primarily based on how the vehicle’s suspension system absorbs and then transmits these movements to the interior and ultimately to the passengers. For certain types of motion, such as rolling, the vehicle’s suspension system can be optimized. For instance, existing active suspension systems, which perform terrain scanning and adjust accordingly to match the terrain [153], can effectively suppress these types of motions, enhancing comfort and potentially reducing the likelihood of motion sickness.

6.5.3 Limitations of the Motion Simulation platform

The thesis utilized two experimental platforms to simulate vehicle motion: a rotating chair and a real vehicle. The former simulated rotational movements, while the latter induced linear movements. Each method has its limitations. The rotating chair is widely used in similar experiments, it allowed for precise control of motion to ensure that each participant experienced the same motion stimuli. This provides a clear baseline of performance for the different cue types. However, its ecological validity is low. For example, the rotating chair cannot fully replicate the true dynamics of a vehicle turning. Regarding real vehicles, their use significantly enhances the ecological validity of experiments. However, driving on public roads introduces additional disturbances and constraints. For instance, vehicle velocity was regulated to 30 mph in compliance with urban area speed limits and ethical guidelines, which restricted the duration of acceleration and deceleration phases, as well as the overall driving profile. This could have contributed to the relatively low levels of motion sickness observed and limited the validation of our design at higher speeds. Additionally, because road conditions are dynamic and include variables such as traffic lights, the variability of traffic, and frequent stops, these factors may have affected participants' motion sickness.

In future studies, real vehicles are still recommended because they improve the ecological validity of the research. If conditions permit, a more controlled road environment would yield more reliable results.

6.5.4 Overall Low Levels of Motion Sickness

For ethical reasons, participants who were likely to be particularly susceptible to motion sickness were screened out, and only mild motion sickness was induced to avoid causing participants severe discomfort or even vomiting. Consequently, the levels of motion sickness exhibited by participants during the experiments were generally low. This limitation affected the ability of the studies to assess the efficacy of treatments for moderate to severe motion sickness. However, since the mitigation methods are based on the theories of motion sickness, our conclusions will remain applicable to individuals who experience greater motion sickness.

6.5.5 Limitations of VR Task Simulations

The thesis employed two types of task to simulate activities within VR: mathematical calculations and VR videos. Both methods are commonly used in similar studies but have their own limitations. The mathematical tasks used in Chapters 3 and 4 have the advantage of being unaffected by participants' cultural or linguistic backgrounds, and the display is controllable, which significantly reduces the onset of cybersickness. However, these tasks do not adequately simulate all common VR use cases involving reading, as users are more engaged in mental calculations than in viewing VR content. Future studies should consider other types of tasks.

The video tasks used in Chapter 5 simulate other common VR applications by focusing on the viewing experience within VR. This approach enhances the realism of the simulated VR environment. However, the introduction of additional video content can potentially increase cybersickness and introduce distractions. This trade-off highlights the challenge of balancing task relevance and the potential for inducing symptoms that could affect the experiment's outcomes. For the VR video tasks, to avoid additional cybersickness induced by the video content, videos with higher vection content were not included in our study. High high vection content may reduce the effectiveness of visual cues in mitigating motion sickness. This is because such video content itself induces motion sickness, and the movement within the video may conflict with the motion perception direction intended by the visual cues, thereby exacerbating sensory conflicts. Further studies should apply the cues from the thesis in this scenario to test effectiveness.

6.6 Conclusion

VR technologies can enhance travel by enabling passengers to engage in Non-Driving Related Tasks such as watching videos, reading or playing games. However, motion sickness may arise and is one of the most significant barriers, negatively impacting the use of VR during travel. There are solutions to this but they can be very visually distracting, getting in the way of the non-driving task that the user wants to perform. This research proposes innovative VR design strategies to mitigate these effects by integrating motion cues that replicate the vehicle's movements, thus reducing sensory conflicts. Visual cues in VR were specifically designed to address the most common rotational and linear movements of vehicles, and studies were conducted in both lab and real-road environments. Results demonstrated that cues designed for rotational movements, as well as acceleration cues for linear movements, could effectively decrease motion sickness without significantly distracting passengers. These findings not only validate the potential of VR to transform passenger experiences by alleviating discomfort without distraction but also contribute to the broader field of spatial computing by providing design guidelines for future VR applications in transportation. This approach ensures a balance between minimising distraction and mitigating motion sickness, marking a significant step forward in the practical application of VR technologies in everyday commuting scenarios.

Bibliography

- [1] Mustufa Abidi, Abdulaziz El-Tamimi, and Abdulrahman Al-Ahmari. Virtual reality: Next generation tool for distance education. *International Journal of Advanced Science and Engineering Technology*, 2(2):95–100, 2012.
- [2] Florian Alt, Dagmar Kern, Fabian Schulte, Bastian Pfleging, Alireza Sahami Shirazi, and Albrecht Schmidt. Enabling micro-entertainment in vehicles based on context information. In *Proceedings of the 2nd international conference on automotive user interfaces and interactive vehicular applications*, pages 117–124, 2010.
- [3] Apple Inc. *iPhone User Guide*, 2023.
- [4] Audi. A showcase becomes a reality: Audi brings VR experience platform to CES 2023. Press release, Dec 15, 2022. Audi showcased VR experience platform that transforms the vehicle interior into a third living space and enables motion-synchronized VR entertainment.
- [5] Lynna J Ausburn and Floyd B Ausburn. Effects of desktop virtual reality on learner performance and confidence in environment mastery: Opening a line of inquiry. *Journal of STEM Teacher Education*, 45(1):6, 2008.
- [6] Lynna J Ausburn and Floyd B Ausburn. Technical perspectives on theory in screen-based virtual reality environments: Leading from the future in vhrd. *Advances in Developing Human Resources*, 16(3):371–390, 2014.
- [7] Gourav Bathla, Kishor Bhadane, Rahul Kumar Singh, Rajneesh Kumar, Rajanikanth Aluvalu, Rajalakshmi Krishnamurthi, Adarsh Kumar, RN Thakur, and Shakila Basheer. Autonomous vehicles and intelligent automation: Applications, challenges, and opportunities. *Mobile Information Systems*, 2022(1):7632892, 2022.
- [8] Stefan Berti and Behrang Keshavarz. Neuropsychological approaches to visually-induced vection: an overview and evaluation of neuroimaging and neurophysiological studies. *Multisensory Research*, 34(2):153–186, 2020.

- [9] Keshav Bimbraw. Autonomous cars: Past, present and future a review of the developments in the last century, the present scenario and the expected future of autonomous vehicle technology. In *2015 12th international conference on informatics in control, automation and robotics (ICINCO)*, volume 1, pages 191–198. IEEE, 2015.
- [10] Willem Bles, Jelte E Bos, Bernd De Graaf, Eric Groen, and Alexander H Wertheim. Motion sickness: only one provocative conflict? *Brain research bulletin*, 47(5):481–487, 1998.
- [11] Jelte E Bos. Optimising human performance by reducing motion sickness and enhancing situation awareness with an intuitive artificial 3d earth-fixed visual reference. In *Maritime Systems and Technologies conference (MAST Europe 2012)*, 2012.
- [12] Jelte E Bos, Scott N MacKinnon, and Anthony Patterson. Motion sickness symptoms in a ship motion simulator: effects of inside, outside, and no view. *Aviation, space, and environmental medicine*, 76(12):1111–1118, 2005.
- [13] Adrian Brietzke, Rebecca Pham Xuan, André Dettmann, and Angelika C Bullinger. Einfluss der dynamischen stimulation, visuellen wahrnehmung und individuellen kinetoseempfindlichkeit auf kinetose im pkw in einer kontrollierten stop-and-go-fahrt. *Forschung im Ingenieurwesen*, 85:517–526, 2021.
- [14] Zelig Britton and Qadeer Arshad. Vestibular and multi-sensory influences upon self-motion perception and the consequences for human behavior. *Frontiers in neurology*, 10:63, 2019.
- [15] Helmut Buhler, Sebastian Misztal, and Jonas Schild. Reducing vr sickness through peripheral visual effects. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 517–9. IEEE, 2018.
- [16] Sonic HY Chan, Reik V Donner, and Stefan Lämmer. Urban road networks—spatial networks with universal geometric features? a case study on germany’s largest cities. *The European Physical Journal B*, 84:563–577, 2011.
- [17] Yu-Chieh Chen, Jeng-Ren Duann, Shang-Wen Chuang, Chun-Ling Lin, Li-Wei Ko, Tzyy-Ping Jung, and Chin-Teng Lin. Spatial and temporal eeg dynamics of motion sickness. *NeuroImage*, 49(3):2862–2870, 2010.
- [18] Yu-nuo Cheng, Xia Zhong, and Li-wei Tian. Does the ar-hud system affect driving behaviour? an eye-tracking experiment study. *Transportation research interdisciplinary perspectives*, 18:100767, 2023.

- [19] Hyung-jun Cho and Gerard J Kim. Roadvr: Mitigating the effect of vection and sickness by distortion of pathways for in-car virtual reality. In *26th ACM Symposium on Virtual Reality Software and Technology*, pages 1–3, 2020.
- [20] Hyung-Jun Cho and Gerard J Kim. Ridevr: Reducing sickness for in-car virtual reality by mixed-in presentation of motion flow information. *IEEE Access*, 10:34003–34011, 2022.
- [21] Burcu Cinaz, Roberto La Marca, Bert Arnrich, Gerhard Tröster, et al. Monitoring of mental workload levels. 2010.
- [22] Ronald A Cohen, Yvonne A Sparling-Cohen, and Brian F O’Donnell. *The neuropsychology of attention*. Springer, 1993.
- [23] Mark Colley, Pascal Jansen, Enrico Rukzio, and Jan Gugenheimer. Swivr-car-seat: Exploring vehicle motion effects on interaction quality in virtual reality automated driving using a motorized swivel seat. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 5(4):1–26, 2021.
- [24] Marc Cranswick and Mark Cranswick. *Pontiac Firebird: The Auto-Biography*. David and Charles, 2003.
- [25] Mary Czerwinski, Greg Smith, Tim Regan, Brian Meyers, George G Robertson, and Gary K Starkweather. Toward characterizing the productivity benefits of very large displays. In *Interact*, volume 3, pages 9–16, 2003.
- [26] Ylli Dalladaku, Jacob Kelley, Brycen Lacey, James Mitchiner, Braden Welsh, and Matthew Beigh. Assessing the effectiveness of virtual reality in the training of army aviators. In *Proceedings of the 2020 Annual General Donald R. Keith Memorial Capstone Conference, New York, NY*, volume 40, 2020.
- [27] Abhraneil Dam and Myounghoon Jeon. A review of motion sickness in automated vehicles. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 39–48, 2021.
- [28] Ksander N de Winkel, Paolo Pretto, Suzanne AE Nooij, Iris Cohen, and Heinrich H Bülthoff. Efficacy of augmented visual environments for reducing sickness in autonomous vehicles. *Applied Ergonomics*, 90:103282, 2021.
- [29] Mark S Dennison, A Zachary Wisti, and Michael D’Zmura. Use of physiological signals to predict cybersickness. *Displays*, 44:42–52, 2016.
- [30] Cyriel Diels. Will autonomous vehicles make us sick. *Contemporary ergonomics and human factors*, pages 301–307, 2014.

- [31] Cyriel Diels, Jelte E Bos, Katharina Hottelart, and Patrice Reilhac. The impact of display position on motion sickness in automated vehicles: an on-road study. In *Automated vehicle symposium, San Francisco*, pages 19–21, 2016.
- [32] Cyriel Diels, Jelte E Bos, Katharina Hottelart, and Patrice Reilhac. Motion sickness in automated vehicles: the elephant in the room. *Road Vehicle Automation 3*, pages 121–129, 2016.
- [33] Cyriel Diels and Peter A Howarth. Frequency characteristics of visually induced motion sickness. *Human factors*, 55(3):595–604, 2013.
- [34] Paul DiZio, Jack Ekchian, Janna Kaplan, Joel Ventura, William Graves, Marco Giovannardi, Zack Anderson, and James R Lackner. An active suspension system for mitigating motion sickness and enabling reading in a car. *Aerospace medicine and human performance*, 89(9):822–829, 2018.
- [35] Barnaby E Donohew and Michael J Griffin. Motion sickness: effect of the frequency of lateral oscillation. *Aviation, space, and environmental medicine*, 75(8):649–656, 2004.
- [36] Sarah D’Amour, Laurence R Harris, Stefan Berti, and Behrang Keshavarz. The role of cognitive factors and personality traits in the perception of illusory self-motion (vection). *Attention, Perception, & Psychophysics*, 83:1804–1817, 2021.
- [37] F Thomas Eggemeier and Glenn F Wilson. Performance-based and subjective assessment of workload in multi-task environments. *Multiple-task performance*, pages 217–278, 2020.
- [38] Ahmed Ibrahim Ahmed Mohamed Elsharkawy, Aya Abdunnasser Saed Ataya, Dohyeon Yeo, Eunsol An, Seokhyun Hwang, and SeungJun Kim. Sync-vr: Synchronizing your senses to conquer motion sickness for enriching in-vehicle virtual reality. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*, pages 1–17, 2024.
- [39] William Emond, Dominique Bohrmann, and Mohsen Zare. Will visual cues help alleviating motion sickness in automated cars? a review article. *Ergonomics*, pages 1–29, 2023.
- [40] PJ Feenstra, Jelte E Bos, and Ronald NHW van Gent. A visual display enhancing comfort by counteracting airsickness. *Displays*, 32(4):194–200, 2011.
- [41] Jason Fischer. The building blocks of intuitive physics in the mind and brain, 2021.
- [42] Liviu A Fodor, Carmen D Coteț, Pim Cuijpers, Ștefan Szamoskozi, Daniel David, and Ioana A Cristea. The effectiveness of virtual reality based interventions for symptoms of anxiety and depression: A meta-analysis. *Scientific reports*, 8(1):10323, 2018.

- [43] Olaya García-Rodríguez, Irene Pericot-Valverde, José Gutiérrez-Maldonado, Marta Ferrer-Garcia, and Roberto Secades-Villa. Validation of smoking-related virtual environments for cue exposure therapy. *Addictive behaviors*, 37(6):703–708, 2012.
- [44] Divya Garikapati and Sneha Sudhir Shetiya. Autonomous vehicles: Evolution of artificial intelligence and the current industry landscape. *Big Data and Cognitive Computing*, 8(4):42, 2024.
- [45] Gregor Geršak, Huimin Lu, and Jože Guna. Effect of vr technology matureness on vr sickness. *Multimedia Tools and Applications*, 79:14491–14507, 2020.
- [46] Guy Godin. Virtual desktop. <https://store.steampowered.com/app/382110/Virtual>, 2017.
- [47] David Goedicke, Alexandra WD Bremers, Sam Lee, Fanjun Bu, Hiroshi Yasuda, and Wendy Ju. Xr-oom: Mixed reality driving simulation with real cars for research and design. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, pages 1–13, 2022.
- [48] John F Golding. Phasic skin conductance activity and motion sickness. *Aviation, space, and environmental medicine*, 63(3):165–171, 1992.
- [49] John F Golding. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. *Brain research bulletin*, 47(5):507–516, 1998.
- [50] John F Golding. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. *Brain research bulletin*, 47(5):507–516, 1998.
- [51] John F Golding. Motion sickness susceptibility. *Autonomic Neuroscience*, 129(1-2):67–76, 2006.
- [52] John F Golding, W Bles, JE Bos, Tamika Haynes, and Michael A Gresty. Motion sickness and tilts of the inertial force environment: active suspension systems vs. active passengers. *Aviation, space, and environmental medicine*, 74(3):220–227, 2003.
- [53] Ashton Graybiel and James Knepton. Sopite syndrome: a sometimes sole manifestation of motion sickness. *Aviation, space, and environmental medicine*, 47(8):873–882, 1976.
- [54] Jeffery B Greenblatt and Susan Shaheen. Automated vehicles, on-demand mobility, and environmental impacts. *Current sustainable/renewable energy reports*, 2:74–81, 2015.
- [55] Michael J Griffin and HVC Howarth. Motion sickness history questionnaire. 2000.
- [56] Michael J Griffin and Maria M Newman. Visual field effects on motion sickness in cars. *Aviation, space, and environmental medicine*, 75(9):739–748, 2004.

- [57] Colin Groth, Jan-Philipp Tauscher, Nikkel Heesen, Max Hattenbach, Susana Castillo, and Marcus Magnor. Omnidirectional galvanic vestibular stimulation in virtual reality. *IEEE transactions on Visualization and Computer Graphics*, 28(5):2234–2244, 2022.
- [58] Evan Hanau and Voicu Popescu. Motionreader: Visual acceleration cues for alleviating passenger e-reader motion sickness. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, AutomotiveUI '17, page 72–76, New York, NY, USA, 2017. Association for Computing Machinery.
- [59] Wanja Hemmerich, Behrang Keshavarz, and Heiko Hecht. Visually induced motion sickness on the horizon. *Frontiers in Virtual Reality*, 1:582095, 2020.
- [60] Wanja A Hemmerich, Avner Shahal, and Heiko Hecht. Predictors of visually induced motion sickness in women. *Displays*, 58:27–32, 2019.
- [61] Philipp Hock, Sebastian Benedikter, Jan Gugenheimer, and Enrico Rukzio. Carvr: Enabling in-car virtual reality entertainment. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, page 4034–4044, New York, NY, USA, 2017. Association for Computing Machinery.
- [62] Sharon R Holmes and Michael J Griffin. Correlation between heart rate and the severity of motion sickness caused by optokinetic stimulation. *Journal of Psychophysiology*, 15(1):35, 2001.
- [63] Zaw Htike, Georgios Papaioannou, Efstathios Siampis, Efstathios Velenis, and Stefano Longo. Motion sickness minimisation in autonomous vehicles using optimal control. In *Advances in Service and Industrial Robotics: Results of RAAD*, pages 275–282. Springer, 2020.
- [64] Doreen Huppert, Judy Benson, and Thomas Brandt. A historical view of motion sickness—a plague at sea and on land, also with military impact. *Frontiers in neurology*, 8:114, 2017.
- [65] Alex D Hwang, Eli Peli, and Jae-Hyun Jung. Development of virtual reality walking collision detection test on head-mounted display. In *Optical Architectures for Displays and Sensing in Augmented, Virtual, and Mixed Reality (AR, VR, MR) IV*, volume 12449, pages 281–289. SPIE, 2023.
- [66] Insurance Institute for Highway Safety. Self-driving vehicles could struggle to eliminate most crashes, June 2020. Accessed: 2025-09-05.

- [67] Julie Iskander, Mohammed Attia, Khaled Saleh, Darius Nahavandi, Ahmed Abobakr, Shady Mohamed, Houshyar Asadi, Abbas Khosravi, Chee Peng Lim, and Mohammed Hossny. From car sickness to autonomous car sickness: A review. *Transportation research part F: traffic psychology and behaviour*, 62:716–726, 2019.
- [68] Naoki Isu, Takuya Hasegawa, Ichiro Takeuchi, and Akihiro Morimoto. Quantitative analysis of time-course development of motion sickness caused by in-vehicle video watching. *Displays*, 35(2):90–97, 2014.
- [69] James Jeng-Weei Lin, DE Parker, Michal Lahav, and TA Furness. Unobtrusive vehicle motion prediction cues reduced simulator sickness during passive travel in a driving simulator. *Ergonomics*, 48(6):608–624, 2005.
- [70] Ole Jensen and Ali Mazaheri. Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Frontiers in human neuroscience*, 4:186, 2010.
- [71] Marshall B Jones, Robert S Kennedy, and Kay M Stanney. Toward systematic control of cybersickness. *Presence: Teleoperators & Virtual Environments*, 13(5):589–600, 2004.
- [72] MICHAEL SIVAK MASAMI AOKI JUHA LUOMA, MICHAEL J. FLANNAGAN and ERIC C. TRAUBE. Effects of turn-signal colour on reaction times to brake signals. *Ergonomics*, 40(1):62–68, 1997.
- [73] Su-min Jung and Taeg-kuen Whangbo. Study on inspecting vr motion sickness inducing factors. In *2017 4th International Conference on Computer Applications and Information Processing Technology (CAIPT)*, pages 1–5. IEEE, 2017.
- [74] Younhyun Jung. Virtual reality simulation for disaster preparedness training in hospitals: integrated review. *Journal of Medical Internet Research*, 24(1):e30600, 2022.
- [75] Juffrizal Karjanto, Nidzamuddin Md Yusof, Muhammad Zahir Hassan, Jacques Terken, Frank Delbressine, and Matthias Rauterberg. An on-road study in mitigating motion sickness when reading in automated driving. *Journal of Hunan University Natural Sciences*, 48(3), 2021.
- [76] Juffrizal Karjanto, Nidzamuddin Md Yusof, Chao Wang, Jacques Terken, Frank Delbressine, and Matthias Rauterberg. The effect of peripheral visual feedforward system in enhancing situation awareness and mitigating motion sickness in fully automated driving. *Transportation research part F: traffic psychology and behaviour*, 58:678–692, 2018.
- [77] Kazuhito Kato and Satoshi Kitazaki. A study for understanding carsickness based on the sensory conflict theory. *SAE technical paper*, 1:0096, 2006.

- [78] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.
- [79] Behrang Keshavarz and Heiko Hecht. Validating an efficient method to quantify motion sickness. *Human factors*, 53(4):415–426, 2011.
- [80] Behrang Keshavarz, Daniela Stelzmann, Aurore Paillard, and Heiko Hecht. Visually induced motion sickness can be alleviated by pleasant odors. *Experimental brain research*, 233(5):1353–1364, 2015.
- [81] Eunjee Kim, Hyunjae Gil, Jiwon Ryu, Ian Oakley, and Gwanseob Shin. The effect of peripheral cues on motion sickness mitigation when using a vr hmd in a car. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 66, pages 1967–1971. SAGE Publications Sage CA: Los Angeles, CA, 2022.
- [82] Hyun K Kim, Jaehyun Park, Yeongcheol Choi, and Mungyeong Choe. Virtual reality sickness questionnaire (vrsq): Motion sickness measurement index in a virtual reality environment. *Applied ergonomics*, 69:66–73, 2018.
- [83] Jiwon Kim, Jihong Hwang, and Taezoon Park. Effect of motion cues on simulator sickness in a flight simulator. In *Virtual, Augmented and Mixed Reality. Design and Interaction: 12th International Conference, VAMR 2020, Held as Part of the 22nd HCI International Conference, HCII 2020, Copenhagen, Denmark, July 19–24, 2020, Proceedings, Part I 22*, pages 493–506. Springer, 2020.
- [84] Andreas Koch, Ingolf Cascorbi, Martin Westhofen, Manuel Dafotakis, Sebastian Klapa, and Johann Peter Kuhtz-Buschbeck. The neurophysiology and treatment of motion sickness. *Deutsches Ärzteblatt International*, 115(41):687, 2018.
- [85] Linghe Kong, Muhammad Khurram Khan, Fan Wu, Guihai Chen, and Peng Zeng. Millimeter-wave wireless communications for iot-cloud supported autonomous vehicles: Overview, design, and challenges. *IEEE Communications Magazine*, 55(1):62–68, 2017.
- [86] Lars Kooijman, Saeid Nahavandi, Houshyar Asadi, and Shady Mohamed. Does a secondary task inhibitvection in virtual reality? In *2022 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 1057–1064. IEEE, 2022.
- [87] John K Kruschke. Bayesian estimation supersedes the t test. *Journal of Experimental Psychology: General*, 142(2):573, 2013.
- [88] Ouren X Kuiper, Jelte E Bos, and Cyriel Diels. Looking forward: In-vehicle auxiliary display positioning affects carsickness. *Applied Ergonomics*, 68:169–175, 2018.

- [89] Ouren X Kuiper, Jelte E Bos, Eike A Schmidt, Cyriel Diels, and Stefan Wolter. knowing what's coming: unpredictable motion causes more motion sickness. *Human factors*, 62(8):1339–1348, 2020.
- [90] Miltos Kyriakidis, Riender Happee, and Joost CF De Winter. Public opinion on automated driving: Results of an international questionnaire among 5000 respondents. *Transportation research part F: traffic psychology and behaviour*, 32:127–140, 2015.
- [91] Ray Lattarulo, Leonardo González, Enrique Martí, José Matute, Mauricio Marciano, and Joshue Pérez. Urban motion planning framework based on n-bézier curves considering comfort and safety. *Journal of Advanced Transportation*, 2018(1):6060924, 2018.
- [92] Esko Lehtonen, Fanny Malin, Tyron Louw, Yee Mun Lee, Teemu Itkonen, and Satu Innamaa. Why would people want to travel more with automated cars? *Transportation research part F: traffic psychology and behaviour*, 89:143–154, 2022.
- [93] Barbara Lenz, Eva-Maria Fraedrich, and Rita Cyganski. Riding in an autonomous car: What about the user perspective? 2016.
- [94] Alexander KC Leung and Kam Lun Hon. Motion sickness: an overview. *Drugs in context*, 8, 2019.
- [95] Rafał Lewkowicz, Bibianna Bałaj, and Piotr Francuz. The incidence of simulator sickness in pilots and non-pilots exposed to spatial disorientation events in the gyro-ipt simulator. *Pol J Aviat Med Bioeng Psychol*, 26(4):13–25, 2020.
- [96] Gang Li, Ari Billig, Chao Ping Chen, and Katharina Pohlmann. Can brain stimulation reduce vr motion sickness in healthy young adults during an immersive relaxation application? a study of tacs. In *2024 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 791–792. IEEE, 2024.
- [97] Gang Li, Tanaya Guha, Ogechi Onuoha, Zhanyan Qiu, Alana Grant, Zejian Feng, Zirui Zhang, Katharina Pohlmann, Mark McGill, Stephen Brewster, et al. Detecting in-car vr motion sickness from lower face action units. In *2024 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 1019–1028. IEEE, 2024.
- [98] Gang Li, Yu-Kai Wang, Mark McGill, Katharina Pöhlmann, Stephen Brewster, and Frank Pollick. Resting-state eeg in the vestibular region can predict motion sickness induced by a motion-simulated in-car vr platform. In *2023 IEEE Symposium Series on Computational Intelligence (SSCI)*, pages 47–52. IEEE, 2023.
- [99] Jingyi Li, Ceenu George, Andrea Ngao, Kai Holländer, Stefan Mayer, and Andreas Butz. Rear-seat productivity in virtual reality: Investigating vr interaction in the confined space of a car. *Multimodal Technologies and Interaction*, 5(4):15, 2021.

- [100] Jingyi Li, Agnes Reda, and Andreas Butz. Queasy rider: How head movements influence motion sickness in passenger use of head-mounted displays. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 28–38, 2021.
- [101] Wei Li, Xiaobo Lu, YiShen Zhang, and Huiya Zhao. How the cognitive styles affect the immersive experience: A study of video-watching experience in vr. In *Design, User Experience, and Usability. User Experience in Advanced Technological Environments: 8th International Conference, DUXU 2019, Held as Part of the 21st HCI International Conference, HCII 2019, Orlando, FL, USA, July 26–31, 2019, Proceedings, Part II 21*, pages 163–177. Springer, 2019.
- [102] Chin-Teng Lin, Chun-Ling Lin, Tzai-Wen Chiu, Jeng-Ren Duann, and Tzyy-Ping Jung. Effect of respiratory modulation on relationship between heart rate variability and motion sickness. In *2011 Annual International Conference of the IEEE engineering in medicine and biology society*, pages 1921–1924. IEEE, 2011.
- [103] Phil Lopes, Nana Tian, and Ronan Boulic. Exploring blink-rate behaviors for cybersickness detection in vr. In *2020 IEEE Conference on virtual reality and 3D user interfaces abstracts and workshops (VRW)*, pages 794–795. IEEE, 2020.
- [104] Zongwei Luo. *Robotics, automation, and control in industrial and service settings*. IGI Global, 2015.
- [105] Jun Ma, Jiateng Li, Wei Wang, Hongwei Huang, Xu Zhang, and Jingyi Zhao. The impact of co-pilot displays use on driver workload and driving performance exploring the impact of co-pilot display on drivers’ workload and driving performance. *Applied Ergonomics*, 114:104138–104138, 2023.
- [106] Robert L Matchock, Max E Levine, Peter J Gianaros, and Robert M Stern. Susceptibility to nausea and motion sickness as a function of the menstrual cycle. *Women’s Health Issues*, 18(4):328–335, 2008.
- [107] Mark McGill, Aidan Kehoe, Euan Freeman, and Stephen Brewster. Expanding the bounds of seated virtual workspaces. *ACM Trans. Comput.-Hum. Interact.*, 27(3), may 2020.
- [108] Mark McGill, Gang Li, Alex Ng, Laura Bajorunaite, Julie Williamson, Frank Pollick, and Stephen Brewster. Augmented, virtual and mixed reality passenger experiences. *User Experience Design in the Era of Automated Driving*, pages 445–475, 2022.
- [109] Mark McGill, Alexander Ng, and Stephen Brewster. I am the passenger: how visual motion cues can influence sickness for in-car vr. In *Proceedings of the 2017 chi conference on human factors in computing systems*, pages 5655–5668, 2017.

- [110] Mark McGill, Julie Williamson, Alexander Ng, Frank Pollick, and Stephen Brewster. Challenges in passenger use of mixed reality headsets in cars and other transportation. *Virtual Reality*, 24:583–603, 2020.
- [111] Mark McGill, Graham Wilson, Daniel Medeiros, and Stephen Anthony Brewster. Passengxr: A low cost platform for any-car, multi-user, motion-based passenger xr experiences. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*, pages 1–15, 2022.
- [112] Daniel Medeiros, Mark McGill, Alexander Ng, Robert McDermid, Nadia Pantidi, Julie Williamson, and Stephen Brewster. From shielding to avoidance: Passenger augmented reality and the layout of virtual displays for productivity in shared transit. *IEEE Transactions on Visualization and Computer Graphics*, 28(11):3640–3650, 2022.
- [113] Alexander Meschtscherjakov, Sebastian Strumegger, and Sandra Trösterer. Bubble margin: Motion sickness prevention while reading on smartphones in vehicles. In *Human-Computer Interaction–INTERACT 2019: 17th IFIP TC 13 International Conference, Paphos, Cyprus, September 2–6, 2019, Proceedings, Part II 17*, pages 660–677. Springer, 2019.
- [114] Markus Miksch, Martin Steiner, Michael Miksch, and Alexander Meschtscherjakov. Motion sickness prevention system (msps) reading between the lines. In *Adjunct Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 147–152, 2016.
- [115] Martin Mondek and Martin Hromčík. Linear analysis of lateral vehicle dynamics. In *2017 21st International Conference on Process Control (PC)*, pages 240–246. IEEE, 2017.
- [116] Kenneth E Money. Motion sickness. *Physiological reviews*, 50(1):1–39, 1970.
- [117] Alberto Morando, Pnina Gershon, Bruce Mehler, and Bryan Reimer. A model for naturalistic glance behavior around tesla autopilot disengagements. *Accident Analysis & Prevention*, 161:106348, 2021.
- [118] Akihiro Morimoto, Naoki Isu, Tomohiro Okumura, Yusuke Araki, Atsuo Kawai, and Fumito Masui. Image rendering for reducing carsickness in watching onboard video display. In *2008 Digest of Technical Papers-International Conference on Consumer Electronics*, pages 1–2. IEEE, 2008.
- [119] Louisa Mordin, John Golding, and Adolfo Bronstein. Managing motion sickness. *Bmj*, 343, 2011.

- [120] Author Name. Why did fuzzy dice become popular in cars? <https://www.meadowlandofcarmel.net/blog/why-did-fuzzy-dice-become-popular-in-cars/>. Accessed: 2025-03-13.
- [121] Sewon Noh, Junseo Park, and Gerard J Kim. Effect of synchronized vehicle motion to mitigating sickness for on-vehicle vr during active task performance. *IEEE Access*, 2024.
- [122] Sewon Noh, Seunghoon Park, and Gerard J Kim. Onvehiclevr: Mitigating sickness in on-vehicle virtual reality by mixing in synchronized vehicle motion information. *IEEE Access*, 2024.
- [123] Eyal Ofek, Jens Grubert, Michel Pahud, Mark Phillips, and Per Ola Kristensson. Towards a practical virtual office for mobile knowledge workers. *arXiv preprint arXiv:2009.02947*, 2020.
- [124] Charles M Oman. Motion sickness: a synthesis and evaluation of the sensory conflict theory. *Canadian journal of physiology and pharmacology*, 68(2):294–303, 1990.
- [125] AC Paillard, Maryam Lamôré, Olivier Etard, J-L Millot, Laurence Jacquot, Pierre Denise, and Gaëlle Quarck. Is there a relationship between odors and motion sickness? *Neuroscience letters*, 566:326–330, 2014.
- [126] Stephen Palmisano, Robert S Allison, and Juno Kim. Cybersickness in head-mounted displays is caused by differences in the user’s virtual and physical head pose. *Frontiers in Virtual Reality*, 1:587698, 2020.
- [127] Stephen Palmisano and Juno Kim. Effects of gaze on vection from jittering, oscillating, and purely radial optic flow. *Attention, Perception, & Psychophysics*, 71(8):1842–1853, 2009.
- [128] Su Han Park, Bin Han, and Gerard Jounghyun Kim. Mixing in reverse optical flow to mitigate vection and simulation sickness in virtual reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, pages 1–11, 2022.
- [129] Eli Peli. The visual effects of head-mounted display (hmd) are not distinguishable from those of desk-top computer display. *Vision research*, 38(13):2053–2066, 1998.
- [130] Kenneth A Perrine, Kara M Kockelman, and Yantao Huang. Anticipating long-distance travel shifts due to self-driving vehicles. *Journal of Transport Geography*, 82:102547, 2020.

- [131] Melissa Peskin, Brittany Mello, Judith Cukor, Megan Olden, and JoAnn Difede. Virtual reality applications to treat posttraumatic stress disorder. In *Virtual Reality for Psychological and Neurocognitive Interventions*, pages 85–102. Springer, 2019.
- [132] Phyllida. Multiscreens vr. <https://store.steampowered.com/app/512400/Multiscreens/>, 2017.
- [133] Amâncio da Costa Pinto. Reading rates and digit span in bilinguals: The superiority of mother tongue. *International Journal of Psychology*, 26(4):471–483, 1991.
- [134] Katharina Pöhlmann, Gang Li, Mark McGill, Reuben Markoff, and Stephen Brewster. You spin me right round, baby, right round: Examining the impact of multi-sensory self-motion cues on motion sickness during a vr reading task. 2023.
- [135] Katharina Margareta Theresa Pöhlmann, Marc Stephan Kurt Auf Der Heyde, Gang Li, Frans Verstraten, Stephen Anthony Brewster, and Mark McGill. Can visual motion presented in a vr headset reduce motion sickness for vehicle passengers? In *Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '22, page 114–118, New York, NY, USA, 2022. Association for Computing Machinery.
- [136] Katharina Margareta Theresa Pöhlmann, Marc Stephan Kurt Auf Der Heyde, Gang Li, Frans Verstraten, Stephen Anthony Brewster, and Mark McGill. Can visual motion presented in a vr headset reduce motion sickness for vehicle passengers? In *Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 114–118, 2022.
- [137] Katharina Margareta Theresa Pöhlmann, Marc Stephan Kurt Auf Der Heyde, Gang Li, Frans Verstraten, Stephen Anthony Brewster, and Mark McGill. Can visual motion presented in a vr headset reduce motion sickness for vehicle passengers? In *Adjunct Proceedings of the 14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '22, page 114–118, New York, NY, USA, 2022. Association for Computing Machinery.
- [138] Katharina Margareta Theresa Pöhlmann, Gang Li, Mark McGill, Reuben Markoff, and Stephen Anthony Brewster. You spin me right round, baby, right round: Examining the impact of multi-sensory self-motion cues on motion sickness during a vr reading task. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, pages 1–16, 2023.
- [139] Katharina Margareta Theresa Pöhlmann, Graham Wilson, Gang Li, Mark McGill, and Stephen Anthony Brewster. From slow-mo to ludicrous speed: Comfortably manipulating the perception of linear in-car vr motion through vehicular translational gain and

- attenuation. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*, pages 1–20, 2024.
- [140] Katharina MT Pöhlmann, Gang Li, Graham Wilson, Mark McGill, Frank Pollick, and Stephen Brewster. Is video gaming a cure for cybersickness? gamers experience less cybersickness than non-gamers in a vr self-motion task. *IEEE Transactions on Visualization and Computer Graphics*, 2024.
- [141] Zhanyan Qiu, Mark McGill, Katharina Margareta Theresa Pöhlmann, and Stephen Anthony Brewster. Manipulating the orientation of planar 2d content in vr as an implicit visual cue for mitigating passenger motion sickness. In *Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 1–10, 2023.
- [142] Zhanyan Qiu, Mark McGill, Katharina Margareta Theresa Pöhlmann, and Stephen Anthony Brewster. Acceleration instead of speed: Acceleration visual cues in vr for reduced motion sickness in linear motion. In *Adjunct Proceedings of the 16th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 56–61, 2024.
- [143] Zhanyan Qiu, Mark McGill, Katharina Margareta Theresa Pöhlmann, and Stephen Anthony Brewster. Augmenting virtual spatial uis with physics-and direction-based visual motion cues to non-disruptively mitigate motion sickness. In *Proceedings of the 2024 ACM Symposium on Spatial User Interaction*, pages 1–10, 2024.
- [144] James T Reason and Joseph John Brand. *Motion sickness*. Academic press, 1975.
- [145] James T Reason and Joseph John Brand. *Motion sickness*. Academic press, 1975.
- [146] Gary E Riccio and Thomas A Stoffregen. An ecological theory of motion sickness and postural instability. *Ecological psychology*, 3(3):195–240, 1991.
- [147] Arnon Rolnick and RE Lubow. Why is the driver rarely motion sick? the role of controllability in motion sickness. *Ergonomics*, 34(7):867–879, 1991.
- [148] Vincenzo Ronca, Francois Brambati, Linda Napoletano, Cyril Marx, Sandra Trösterer, Alessia Vozzi, Pietro Aricò, Andrea Giorgi, Rossella Capotorto, Gianluca Borghini, et al. A novel eeg-based assessment of distraction in simulated driving under different road and traffic conditions. *Brain sciences*, 14(3):193, 2024.
- [149] KELLOGG RS, KENNEDY RS, and Ashton Graybiel. Motion sickness symptomatology of labyrinthine defective and normal subjects during zero gravity maneuvers. *Aerospace medicine*, 36:315–318, 1965.

- [150] Spencer Salter, Cyriel Diels, Paul Herriotts, Stratis Kanarachos, and Doug Thake. Motion sickness in automated vehicles with forward and rearward facing seating orientations. *Applied ergonomics*, 78:54–61, 2019.
- [151] Taishi Sawabe, Masayuki Kanbara, and Norihiro Hagita. Diminished reality for acceleration—motion sickness reduction with vection for autonomous driving. In *2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*, pages 297–299. IEEE, 2016.
- [152] Yuki Sawada, Yoshihiro Itaguchi, Masami Hayashi, Kosuke Aigo, Takuya Miyagi, Masayuki Miki, Tetsuya Kimura, and Makoto Miyazaki. Effects of synchronised engine sound and vibration presentation on visually induced motion sickness. *Scientific reports*, 10(1):7553, 2020.
- [153] AA Shafie, MM Bello, and RM Khan. Active vehicle suspension control using electro hydraulic actuator on rough road terrain. *Journal of Advanced Research*, 9(1):15–30, 2015.
- [154] William J Shelstad, Dustin C Smith, and Barbara S Chaparro. Gaming on the rift: How virtual reality affects game user satisfaction. In *Proceedings of the human factors and ergonomics society annual meeting*, volume 61, pages 2072–2076. SAGE Publications Sage CA: Los Angeles, CA, 2017.
- [155] Gulbadan Sikander and Shahzad Anwar. Driver fatigue detection systems: A review. *IEEE Transactions on Intelligent Transportation Systems*, 20(6):2339–2352, 2018.
- [156] Michael Sivak and Brandon Schoettle. Motion sickness in self-driving vehicles. Technical report, University of Michigan, Ann Arbor, Transportation Research Institute, 2015.
- [157] Samuel G Solomon and Adam Kohn. Moving sensory adaptation beyond suppressive effects in single neurons. *Current biology*, 24(20):R1012–R1022, 2014.
- [158] State Farm. State farm releases autonomous vehicles survey results, 2024. Accessed: 2024-12-12.
- [159] Andrew H Stevens and Thomas Butkiewicz. Reducing seasickness in onboard marine vr use through visual compensation of vessel motion. In *2019 IEEE conference on virtual reality and 3D user interfaces (VR)*, pages 1872–1873. IEEE, 2019.
- [160] Thomas A Stoffregen, Randy J Pagulayan, Benoit G Bardy, and Lawrence J Hettinger. Modulating postural control to facilitate visual performance. *Human movement science*, 19(2):203–220, 2000.

- [161] Jared D Stokes, Albert Rizzo, Joy J Geng, and Julie B Schweitzer. Measuring attentional distraction in children with adhd using virtual reality technology with eye-tracking. *Frontiers in virtual reality*, 3:855895, 2022.
- [162] Tsukasa Suwa, Yuki Sato, and Takahiro Wada. Reducing motion sickness when reading with head-mounted displays by using see-through background images. *Frontiers in Virtual Reality*, 3:910434, 2022.
- [163] Niels A Taatgen, Marieke K van Vugt, Jeroen Daamen, Ioanna Katidioti, Stefan Huijser, and Jelmer P Borst. The resource-availability model of distraction and mind-wandering. *Cognitive Systems Research*, 68:84–104, 2021.
- [164] David W Temple. *GM’s Motorama: the glamorous show cars of a cultural phenomenon*. MBI Publishing Company, 2006.
- [165] Nikolas Thomopoulos, Scott Cohen, Debbie Hopkins, Lauren Siegel, and Simon Kimber. All work and no play? autonomous vehicles and non-commuting journeys. *Transport Reviews*, 41(4):456–477, 2021.
- [166] Jason Thompson, Mark Stevenson, Jasper S Wijnands, Kerry A Nice, Gideon DPA Aschwanden, Jeremy Silver, Mark Nieuwenhuijsen, Peter Rayner, Robyn Schofield, Rohit Hariharan, et al. A global analysis of urban design types and road transport injury: an image processing study. *The Lancet Planetary Health*, 4(1):e32–e42, 2020.
- [167] Henry Togwell, Mark McGill, Graham Wilson, Daniel Medeiros, and Stephen Anthony Brewster. In-car gaming: Exploring the use of ar headsets to leverage passenger travel environments for mixed reality gameplay. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*, pages 1–7, 2022.
- [168] Osamu Tokumaru, Kenichi Kaida, Hiroshi Ashida, Ikuo Yoneda, and Jiro Tatsuno. Eeg topographical analysis of spatial disorientation. *Aviation, space, and environmental medicine*, 70(3 Pt 1):256–263, 1999.
- [169] Wen-Jie Tseng, Elise Bonnail, Mark McGill, Mohamed Khamis, Eric Lecolinet, Samuel Huron, and Jan Gugenheimer. The dark side of perceptual manipulations in virtual reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, pages 1–15, 2022.
- [170] Mark Turner and Michael J Griffin. Motion sickness in public road transport: the effect of driver, route and vehicle. *Ergonomics*, 42(12):1646–1664, 1999.
- [171] UK Department for Transport. Transport statistics great britain 2022: Domestic travel, 2022. Accessed: 2025-04-09.

- [172] Volvo Cars. 360c Concept — A vision for autonomous, electric, connected and safe travel. Press release, Sep 5, 2018. The concept presents four potential uses: sleeping environment, mobile office, living room, entertainment.
- [173] P Vorderer, Will das Publikum neue Medien, and Medienpsychologische Thesen. Steuer, j.(1992): Defining virtual reality: Dimensions determining telepresence. *journal of communication*, 42, 73-93. straubhaar, j. & larose, r.(1996): Communications media in the information society. belmont, ca: Wadsworth press. turing, a.(1950): Computing machinery and intelligence. *mind*, 59, 433-460.
- [174] Takahiro Wada, Satoru Fujisawa, and Shunichi Doi. Analysis of driver's head tilt using a mathematical model of motion sickness. *International Journal of Industrial Ergonomics*, 63:89–97, 2018.
- [175] Takahiro Wada, Satoru Fujisawa, Katsuya Imaizumi, Norimasa Kamiji, and Shun'ichi Doi. Effect of driver's head tilt strategy on motion sickness incidence. *IFAC Proceedings Volumes*, 43(13):192–197, 2010.
- [176] Takahiro Wada, Hiroyuki Konno, Satoru Fujisawa, and Shun'ichi Doi. Can passengers' active head tilt decrease the severity of carsickness? effect of head tilt on severity of motion sickness in a lateral acceleration environment. *Human factors*, 54(2):226–234, 2012.
- [177] Takahiro Wada and Keigo Yoshida. Effect of passengers' active head tilt and opening/closure of eyes on motion sickness in lateral acceleration environment of cars. *Ergonomics*, 59(8):1050–1059, 2016.
- [178] Alexander D Walker, Eric R Muth, Fred S Switzer, and Adam Hoover. Head movements and simulator sickness generated by a virtual environment. *Aviation, space, and environmental medicine*, 81(10):929–934, 2010.
- [179] Chen Wang, Song-Hai Zhang, Yizhuo Zhang, Stefanie Zollmann, and Shi-Min Hu. On rotation gains within and beyond perceptual limitations for seated vr. *IEEE transactions on visualization and computer graphics*, 29(7):3380–3391, 2022.
- [180] LA1 Warwick-Evans, N Symons, T Fitch, and L Burrows. Evaluating sensory conflict and postural instability. theories of motion sickness. *Brain research bulletin*, 47(5):465–469, 1998.
- [181] Séamas Weech, Sophie Kenny, and Michael Barnett-Cowan. Presence and cybersickness in virtual reality are negatively related: a review. *Frontiers in psychology*, 10:158, 2019.

- [182] Carolin Wienrich and Kristina Schindler. Challenges and requirements of immersive media in autonomous car: Exploring the feasibility of virtual entertainment applications. *i-com*, 18(2):105–125, 2019.
- [183] Graham Wilson, Katharina Margareta Teresa Pöhlmann, David Al Baiaty Suarez, Mark McGill, and Stephen Anthony Brewster. The spin doctor: Leveraging insensitivity to passive rotational & translational gain for unbounded motion-based vr experiences. 2025.
- [184] Wei Yan, Wang Xiang, SC Wong, Xuedong Yan, YC Li, and Wei Hao. Effects of hands-free cellular phone conversational cognitive tasks on driving stability based on driving simulation experiment. *Transportation research part F: traffic psychology and behaviour*, 58:264–281, 2018.
- [185] Fang You, Yang Li, Ronald Schroeter, Jürgen Friedrich, and Jianmin Wang. Using eye-tracking to help design hud-based safety indicators for lane changes. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, pages 217–221, 2017.
- [186] Zhou Yu, Dejing Xu, Jun Yu, Ting Yu, Zhou Zhao, Yueting Zhuang, and Dacheng Tao. Activitynet-qa: A dataset for understanding complex web videos via question answering. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 33, pages 9127–9134, 2019.
- [187] Lishengsa Yue, Mohamed Abdel-Aty, Yina Wu, and Ling Wang. Assessment of the safety benefits of vehicles’ advanced driver assistance, connectivity and low level automation systems. *Accident Analysis & Prevention*, 117:55–64, 2018.
- [188] Nidzamuddin Md Yusof, Juffrizal Karjanto, Muhammad Zahir Hassan, Jacques Terken, Frank Delbressine, and Matthias Rauterberg. Reading during fully automated driving: a study of the effect of peripheral visual and haptic information on situation awareness and mental workload. *IEEE transactions on intelligent transportation systems*, 23(10):19136–19144, 2022.
- [189] Przemysław Zawadzki, Krzysztof Żywicki, Paweł Buń, and Filip Górski. Employee training in an intelligent factory using virtual reality. *IEEE Access*, 8:135110–135117, 2020.
- [190] Li-Li Zhang, Jun-Qin Wang, Rui-Rui Qi, Lei-Lei Pan, Min Li, and Yi-Ling Cai. Motion sickness: current knowledge and recent advance. *CNS neuroscience & therapeutics*, 22(1):15–24, 2016.
- [191] Yahui Zhang, Haohan Zhao, Chuan Hu, Yang Tian, Ying Li, Xiaohong Jiao, and Guilin Wen. Mitigation of motion sickness and optimization of motion comfort in autonomous

vehicles: Systematic survey. *IEEE Transactions on Intelligent Transportation Systems*, 25(12):21737–21756, 2024.

- [192] Haohan Zhao, Mingxin Kang, and Yahui Zhang. Optimal control of active suspension considering mitigating motion sickness in automated vehicles. In *2023 62nd Annual Conference of the Society of Instrument and Control Engineers (SICE)*, pages 43–47. IEEE, 2023.