# Manipulating the Orientation of Planar 2D Content in VR as an Implicit Visual Cue for Mitigating Passenger Motion Sickness

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The use of Virtual Reality technology in vehicles is poised to bring about a new era of transport experiences, but its use can cause or enhance motion sickness. However, with careful design, VR devices have the potential to mitigate motion sickness and provide immersive experiences while travelling. We propose a novel implicit motion cue for manipulating a virtual display presented in Virtual and Extended Reality. Our design mitigates motion sickness by providing awareness of physical orientation changes through changes in the visual orientation of the virtual planar content. We performed two experiments on a rotating chair, testing mitigation properties of different levels of rotational gain applied to the display. Our results showed that the technique significantly reduced motion sickness, without negatively affecting task performance. Our findings show that we can subtly interleave motion cues in existing spatial content like planar displays and this can contribute to lessening motion sickness experienced.

CCS Concepts: • **Human-centered computing → Virtual reality**.

Additional Key Words and Phrases: Virtual Reality, Motion sickness, 1DoF motion platform

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## 1 INTRODUCTION

As autonomous driving evolves and flourishes, it is anticipated that the frequency of in vehicle travel will increase [46]. The advent of Autonomous Vehicles (AVs) will lead to drivers transitioning into passengers [46] optimising their travel time for non-driving related activities. Existing in-vehicle entertainment and productivity rely on physical mobile displays like smartphones, laptops, and tablets. However, they are limited in terms of size, shape, positioning and consequent ergonomics [35], and also pose challenges in terms of privacy. The advent of Virtual Reality (VR) and Extended Reality (XR) technology offers the potential to revolutionise the way in which we interact with digital content and represents a promising next-generation computing platform [2], breaking free from the constraints of existing physical mobile and integrated displays [35]. Such headsets will be able to render 2D planar productivity apps (e.g. word processors, web browsers, *Virtual Desktops*) and entertainment content (e.g. television, movies) at any size, position, and depth relative to the user, potentially creating a more enjoyable and ergonomic travel experience for passengers.

However, using an XR headset while in a moving vehicle could increase the likelihood of experiencing motion sickness. A possible explanation is that motion sickness is caused by the mismatch of the visual and vestibular systems [51]. When travelling in AVs, drivers become passengers [46], with passengers often engaging in Non-Driving Related Tasks (NDRTs, e.g. reading, watching movies, working). Their visual attention is commonly focused on the car's interior or on electronic devices, perceiving stationary visual information while the vestibular system receives information about the vehicle's physical motion, which can result in motion sickness. Wearing a XR headset may occlude any perceivable visual information that matches the passenger's physically-perceived self-motion. Moreover, excessive passenger head movements when viewing virtual spatial content around them could also increase the risk of motion sickness [31, 55–58].

On the other hand, an XR headset could present visual or multimodal information about the outside world to help resolve this sensory mismatch [50, 51, 62] and be used as a tool for motion sickness mitigation. For example, we can present visual stimuli, such as optic flow patterns conveying motion information from the external environment in the background to reduce conflicts between sensory systems and enhance passenger situational awareness [36]. Additionally, we 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 [15]) and guiding their head tilt/rotation. However, the question of how best to convey vehicle motion in VR to reduce motion sickness remains open. Results show that displaying additional visual cues in VR that are congruent with the physically perceived motion of the passenger can slow the buildup of motion sickness [6, 50]. Presenting visual motion cues that are congruent with the physical motion of the vehicle, and therefore the motion of the passenger, have been used in research [7, 8, 25, 29, 36, 49, 50] as well as commercial applications, such as Holoride [1] to reduce motion sickness and improve enjoyment. However, the use of additional visual cues may compromise user experience by negatively impacting immersion and causing distraction [36]. This motivates the need for motion cue designs that are less invasive and more integrated into the scene or content being experienced, to reduce any impact on distraction/immersion whilst retaining mitigation efficacy.

In this study, we developed a planar 2D virtual display for presenting virtual productivity/entertainment content. To be useful, such a display would occupy the majority of the available visual field in the headset, posing problems for the delivery and effectiveness of existing motion cues. Moreover, these cues could be distracting, for example displaying movement across the peripheral visual field could disturb the reading of content or the watching of a movie. Our novel approach subtly manipulates the virtual planar display (hereafter referred to as the display) itself to convey information about motion implicitly interleaved with the VR content. Our display design provides a visual cue of the experienced rotational motion of the passenger through changes in its yaw orientation. These changes in orientation of the display are relative to the user based on vehicle orientation changes and will aid a reduction in head rotations. The manipulation also offers the potential benefit of reducing the orientation change experienced by the passenger during the turning of a vehicle, with display movements minimising the overall orientation change experienced during a turn.

In this paper, we explore whether the rotation of the rectangular planar interface around the user in VR is an effective visual cue and could slow the onset and severity of motion sickness. A first experiment was conducted in which we examined the performance of two levels of rotational ratios (0.3 and 0.6) applied to the display and their effects on motion sickness. The experiment highlighted the beneficial effects of the smaller ratio. Building upon Experiment 1, we refined the study design for Experiment 2 and tested the 0.3 ratio again. Experiment 2 was performed as a multi-session study, with all conditions being performed for increased durations to induce stronger motion sickness and on separate days to avoid cumulative effects of motion sickness. The 0.3 ratio again significantly reduced the symptoms of motion sickness. Our findings suggest this design can mitigate the onset of motion sickness, motivating future research in the design of motion cues implicitly interleaved with virtual-spatial content for VR use in moving vehicles.

## 2 RELATED WORK

### 2.1 Future Entertainment and Productivity NDRTs in Vehicles

*2.1.1 Limitations of Current In-Vehicle NDRTs.* Many individuals spend a considerable amount of time travelling and commuting in vehicles. As autonomous driving technology becomes more widespread, many drivers will become passengers [46]. Passengers will want to spend their time in the vehicle productively or by engaging in some form of entertainment. To do so at present, people primarily rely on physical displays such as in-car screens or smartphones for interaction. However, this type of interaction has numerous limitations. The size of these physical displays is constrained by the limitations of vehicle space [39]. Furthermore, individuals are often forced to make trade-offs between maintaining privacy and achieving optimal visibility angles in public transport like buses [60]. The change from being a driver to a passenger 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 [21], which can lead to more motion sickness due to decreased situational awareness and perceived control [21, 38] as well as them performing body and head movements that are more likely to enhance sickness [56–58]. Thus, passengers need a more comfortable, ergonomic way to play and work while travelling that does not unduly contribute to their experience of motion sickness.

*2.1.2 Using XR to Present 2D Planar Content.* Czerwinski *et al.* [10] found that a larger and wider display space could enhance the performance of productivity tasks. However, the size of physical displays utilised by passengers is constrained by the limitations of vehicle interior [39]. In contrast, XR headsets are able to render content of any size, at any depth/position, around the passenger. Given this capability, developers and researchers are actively investigating the presentation of 2D planar content on XR devices. This content can include the display of existing streaming videos [33], such as television or movies, to offer an immersive experience, as well as increasing screen size or utilizing multiple screens to display productivity-related content and workspaces [3, 4, 35, 45]. Consequently, XR headsets can enable users to break free from the constraints of mobile devices such as smartphones or laptops, utilizing the surrounding space for content display purposes with enhanced comfort/ergonomics [35, 44]. However, passenger use of VR/XR headsets poses a number of challenges around motion sickness incidence, social acceptability, and interaction in constrained spaces [34] in particular. Foremost of these when considering the presentation of 2D planar content is motion sickness, whose symptoms are unpleasant and can persist for hours after onset, making the rest of the journey uncomfortable for users and depriving them of productive travel time [13].

### 2.2 Motion Sickness

*2.2.1 Mismatch Between Visually and Vestibularly Perceived Self-motion.* Motion sickness is a state of discomfort many people have experienced. It has physical symptoms such as nausea, dizziness, cold, and vomiting [30]. It is widely believed that motion sickness is caused by the mismatch of the visual and vestibular systems. The vestibular system of the human inner ear is composed of otolith organs and semicircular canals used to sense gravity and horizontal/vertical rotation [24]. It is widely accepted that motion sickness has three primary factors: the attributes of the stimulus, the individual susceptibility, and the duration of exposure to the stimulus [51]. While travelling inside vehicles, passengers experience different stimuli throughout the journey and potentially over a long exposure time, so motion sickness can be a serious problem. An example of motion sickness caused by using electronic devices with screens in vehicles can be seen in Morimoto *et al.* [22] - motion sickness is aggravated by watching a movie in a moving vehicle as the information conflict between visual and vestibular systems.

*2.2.2 Lack of Control and Situational Awareness.* There is a general belief that passengers are more prone to motion sickness compared to drivers [52], mainly due to their lack of control and situational awareness. The absence of a traditional driver in autonomous vehicles may further increase the occurrence of motion sickness in AVs. This trend is not unique to vehicles, as similar occurrences have been observed in other motion platforms, such as aeroplanes [23]. Karjanto *et al.* [25] introduced the Peripheral Visual Feedforward System (PVFS), which displays the direction of the next turn using LED lights on both sides of the user. This improves passengers' situational awareness of the vehicle's future motion, reducing the impact of motion sickness. Xiao *et al.* [61] similarly noted that utilizing a sparse peripheral display could improve situational awareness and assist in mitigating motion sickness.

*2.2.3 Physical Head Posture.* As noted earlier, passengers are more prone to motion sickness than drivers [52]. Wada *et al.* [55–58] provided a new explanation by proposing that the strategy for head tilting differed between drivers and passengers, which impacted 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 [12, 29] as well as due to them potentially occluding visual information from their surrounding, thereby creating a conflict between visual and vestibular-perceived self-motion.

### 2.3 Motion Sickness Mitigations

*2.3.1 Explicit Matched Motion and Visual/Multimodal Motion Cues.* Numerous studies have focused on the conflict theory of motion sickness and have designed explicit Visual/Multimodal Motion Cues that correspond with motion to alleviate motion sickness. For instance, Sawabe *et al.* [53] conducted an experiment in which they induced a vector illusion prior to actual acceleration, triggering participants' anticipated response to the 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. For common movements during vehicle motion, such as turning, we require additional countermeasures. Therefore, alternative techniques have been developed that support a wider range of motion types. Miksch *et al.* [41] projected a real-time video stream of the driving environment onto the background of the text while passengers were reading. This allowed passengers to maintain a match between their vestibular and visual information even while reading. These system helps to reduce motion sickness while the techniques are limited to the vehicle platform itself or can only display specific text content. Additionally, many studies have demonstrated that it is possible to reduce motion sickness through different methods to deliver congruent sensory information while using a VR head-mounted display. As McGill *et al.* [36] demonstrated, motion sickness is minimized by matching the movement conveyed by a VR headset with the movement perceived by the actual body. According to Cho *et al.* [6], constantly changing a virtual road according to the vehicle's movement can match the vestibular sense as closely as possible. Consequently, the motion sickness level was reduced. Hock *et al.* [19] demonstrated a technique that maps vehicle motion to the VR world for presenting visual information. This allows users to experience the momentum generated during riding within the VR experience. They proved that the users' level of nausea was reduced. A similar effect can be achieved with auditory cues, as described by Pohlmann *et al.* [50]. Their research findings suggested that visual cues could alleviate symptoms of motion sickness, while the combination of visual and auditory cues further reduced motion sickness and improved passenger experience. This underscores the potential of combining multiple kinds of cues to reduce motion sickness.

*2.3.2 Implicit Motion Cues through Manipulating Presented Content.* A growing body of research has examined how motion cues could be interleaved into the content being consumed, primarily focusing on content rendered on physical flat-panel displays. Meschtscherjakov *et al.* [40] presented the *Bubble Margin*, which shows visual bubble cues on the smartphone's border and had a mitigating effect on motion sickness during reading tasks and can be used as an overlay for any application. Furthermore, Morimoto *et al.* [42] proposed two approaches to reduce motion sickness while watching videos in a vehicle. They demonstrated that distorting or moving the video to reflect the vehicle's motion effectively reduced motion sickness. *MotionReader*, developed by Hanau and Popescu [17], features a similar design. They investigated the effectiveness of different visual cues on e-readers. They designed *Text Inertia*, which conveys acceleration information by moving the virtual border in an e-reader to the opposite direction of the acceleration. Although their experiment did not yield significant improvements, they believed that simulating through an augmented reality virtual window is worth exploring. In our study, we build upon these research insights by contributing a new approach to implicitly conveying rotational motion cues. We do so by manipulating the orientation of presented 2D planar content in real-time based on experienced external motion, as rendered using a VR headset, expanding our capability to interleave visual motion cues with NDRTs.

## 3 EXPERIMENT DESIGN

### 3.1 Experimental Platform

Both studies in this paper used a RotoVR rotating chair (www.rotovr.com) that can do 1 Degree of Freedom rotation around the yaw-axis as a way to induce motion sickness. This platform has already been proven in other studies to induce motion sickness [50]. 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 [5]. 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. We used the Meta Quest 2 headset (www.meta.com/gb/quest/products/quest-2) as the VR platform. Throughout the experiment, participants were wearing the VR headset while seated on the rotating chair, see Figure 1 left. This experiment was approved by the University Ethics Committee.

For Experiment 1, there were a total of 3 conditions, with each condition set to 5 minutes to accumulate motion sickness. In Experiment 2, we further refined and tested our design under increased duration of experienced rotational motion.

### 3.2 Measurement Method

*3.2.1 Motion Sickness Measurement.* Two methods for measuring motion sickness were used. The first was the Simulation Sickness Questionnaire (SSQ, [27]). 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. In our study, the overall score of the SSQ and the Nausea subscale, which is most closely related to motion sickness symptoms, were used to assess the severity of motion sickness in participants. The second method was a 7-point real-time motion sickness rating slider. The slider was from [16] and was displayed at the bottom of the VR screen throughout the experiment.

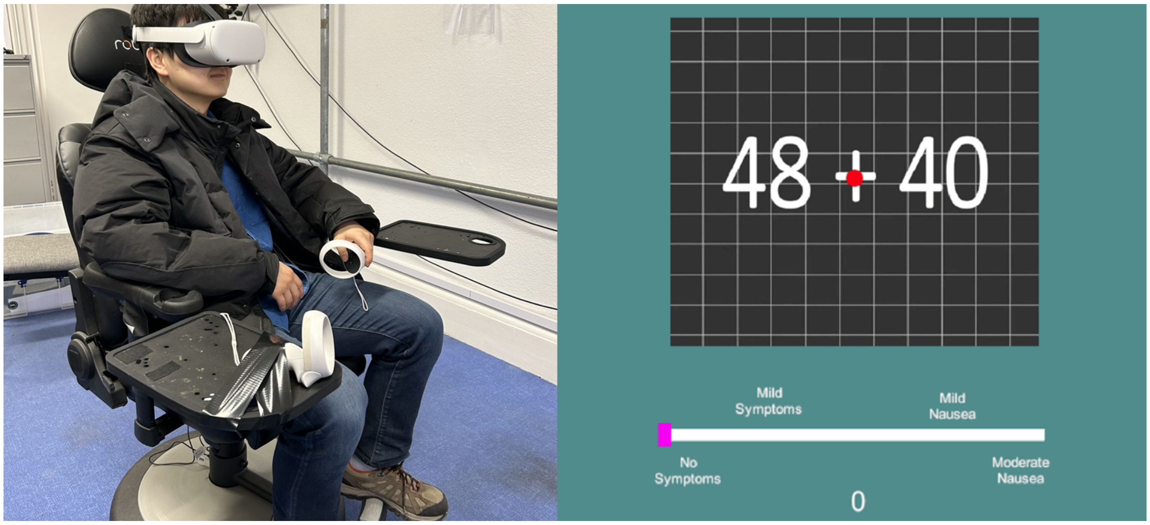


Fig. 1. A participant undergoing rotational motions on the *RotoVR* chair. A screenshot is shown, which mirrors the participant's visual display. The display presents a maths question, a red dot from the attention task, and a slider is provided to allow the participant to indicate their real-time level of motion sickness.

Participants could continuously rate their motion sickness using the slider. The maximum value of this slider was used to reflect the participant's peak level of discomfort experienced during the experiment. The average value of the slider reflected the participant's overall status throughout 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 value. If a participant's rating reached a value of 7 (moderate nausea), the experiment was terminated to ensure the participant's safety. Before participating in the experiment, participants were informed about this threshold.

*3.2.2 Productivity Measurement.* We used a maths task involving two-digit addition and subtraction for the primary task, simulating a productivity activity. Similar maths tasks have been widely used in previous studies as an assessment of participants' cognitive ability and workload capacity [9, 14]. Participants were instructed to provide the answer verbally for each question as quickly as possible. The questions were updated every seven seconds and no answer was counted as a wrong answer. The task was chosen because it is fair to all participants regardless of their language backgrounds, avoiding the disadvantage of non-native speakers with slower reading speeds in tasks involving text [48]. Additionally, we implemented a secondary attention task that required participants to press the trigger on the VR controller when a 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 [28].

### 3.3 Visual Cues for Motion Sickness Mitigation

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 1. As the content of the VR background, such as the virtual horizon [18], can influence motion sickness, we opted to set the background to a solid colour in order to avoid these disturbances. The black background of the task plane was enhanced with white grid lines to make the entire interface more prominent and enhance rotations applied to the display. The rotation of the 2D plane around the participant was used as a visual cue to alleviate motion sickness. Taking the example of the chair rotated by 90°, the participant's field of view sitting on the chair would gradually rotate to the right by 90° as well. When the 2D plane was not rotated, however, due to relative motion, the participant would perceive the 2D plane gradually rotating to the left in their field of view. This would serve as a clear visual cue to match the vestibular motion. However, this rotation would make the 2D plane exceed the VR device's field of view [20]. 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 display plane. 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 2 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 [32, 43, 59]. The value of 0.3 was selected as a compromise between 0.6 and coefficient 0 (where the planar display would be rotated out of the field of view). 0.3 would increase the rotation angle of the display compared to 0.6, but would still be visible. This was made to investigate whether larger or smaller rotation angles would be effective for providing enough motion information. 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 their head faced forward.

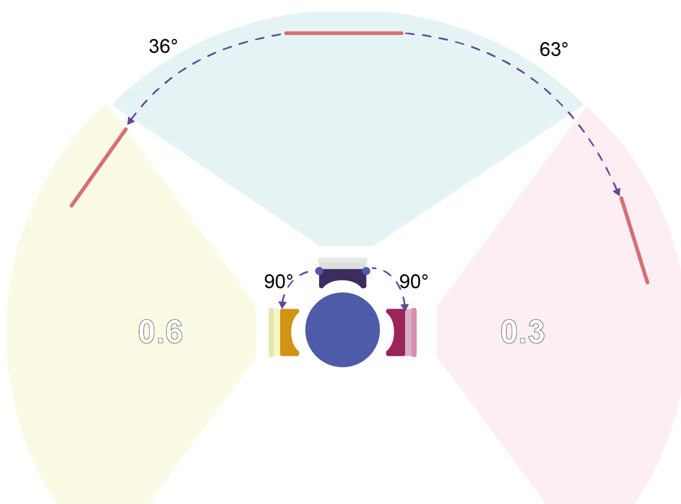


Fig. 2. A top-down view of the visual cue movement. The shaded area represents the VR field of view, and the red line depicts the top-down view of the 2D task plane. The user is at the centre, sat on the *RotoVR* rotating chair. In the case shown on the right, the coefficient X was set to 0.3, with both 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° $(90 - 90 \times 0.6)$.

# 4 EXPERIMENT 1

## 4.1 Experiment Procedure

Experiment 1 consisted of three conditions: A Control condition, where the coefficient was set to 0, meaning that the task plane was rotated to the same degree as the chair rotated; and two experimental conditions: Condition 0.3, which entailed rotating the task plane in the same direction to that of the chair with a coefficient of 0.3; and Condition 0.6, which also involved rotating the task plane, but with a coefficient of 0.6. 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 [47] to minimize order effects.

First, participants undertook a training session 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 participants' 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 of motion sickness 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 have any of the symptoms listed on the SSQ.

## 4.2 Participants

A total of 21 participants took part in Experiment 1: 11 males, 9 females, and one individual identifying as a third gender. No participants dropped out due to the slider value reaching the threshold. Participants ranged in age from 21 to 28 years (M = 24.19, SD = 2.04) and 14 of them had prior experience with VR. To protect participants, anyone with a history of severe motion sickness was excluded from the study. At the beginning of the experiment, participants reconfirmed whether they fully met the experimental requirements.

## 4.3 Results

Our design resulted in motion sickness across all conditions. As the data did not meet the assumption of normality, we employed Friedman's ANOVA as a non-parametric statistical analysis, followed by Pairwise Comparisons tests with Bonferroni correction for *post hoc* comparisons among the different experimental conditions.

*4.3.1 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), $\chi^2(2) = 4.33, p = .115$.

*4.3.2 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)), $\chi^2(2) = 4.46, p = .108$.

*4.3.3 SSQ Nausea Subscale.* The Nausea subscale of the SSQ was analyzed separately because it is the measure 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 significant differences in Nausea between the Control condition (M = 24.07, SD = 20.15) and Condition 0.3(M = 10.44, SD = 11.64, p = .010), see Figure 3.

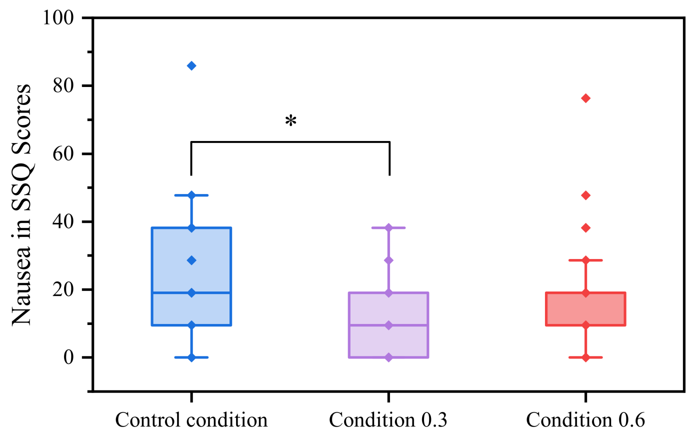


Fig. 3. The Nausea related symptoms subscale from the SSQ in Experiment 1. There was a significant difference between the Control and 0.3 conditions.

*4.3.4 Total SSQ scores.* Total SSQ scores differed significantly between conditions, $\chi^2(2) = 6.07$, p = .048. However, *post hoc* tests revealed that when compared to Control condition (M = 33.84, SD = 29.05), there were no significant differences in neither Condition 0.3 (M = 19.23, SD = 16.86, p = .062) nor Condition 0.6 (M = 32.06, SD = 31.12, p = 1.000) .

*4.3.5 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%).

*4.3.6 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).

*4.3.7 Experiment 1 Discussion.* The results of Experiment 1 demonstrate that our display manipulation with the coefficient of 0.3 was able to significantly reduce adverse symptoms as found for the Nausea subscale of the SSQ. However, we did not observe any such beneficial effects for the other measures. Rotation of the 2D plane also did not have any effects on performance on the maths task or on the attention task, suggesting that rotation of the display at either coefficient level did not affect its usability.

One limitation of the experimental design was that all conditions were conducted within a single day. This meant that motion sickness symptoms may have accumulated across each condition, which may have affected the later conditions more than the earlier ones. We tried to minimise these ordering effects by 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 dropped back to a baseline level, but there may have been some accumulation that was not reported. To overcome this, we conducted Experiment 2 in which all experimental conditions were performed on separate days to avoid any accumulation of motion sickness. This design allowed us to validate our results under conditions of lower interference.

The 0.6 coefficient condition did not significantly reduce motion sickness compared to the Control condition. This may be related to the task plane's reset design. During some larger-angle rotations, the task plane moves to the extreme left or right of the participant's field of view due to the parameter being set at 0.6. When the rotation stops, the task plane resets to the centre of the participant's field of view, which may cause additional mismatch between visual and motion information. In future work, we will further explore the causes of this phenomenon and optimise our design, for example by blinking out the reset rather than having the display move back towards the centre. We decided not to test 0.6 in the second experiment due to the time taken to run the experimental conditions on separate days, so only re-tested the 0.3 condition which had shown a significant effect on motion sickness.

## 5 EXPERIMENT 2

### 5.1 Experiment Procedure

In Experiment 2, we wanted to validate the results of the 0.3 coefficient from Experiment 1, which significantly reduced the effects of nausea and remove any accumulation of motion sickness. A further aim was to test the effectiveness of our motion sickness mitigation on 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 was the same as Experiment 1, and experimental condition which used the same 0.3 coefficient as before. Before each condition, participants answered the SSQ questionnaire to ensure the absence of motion sickness-related symptoms.

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 Experiment 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. The maths task, motion sickness slider and attention task were the same as for Experiment 1. 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 rate their symptoms.

### 5.2 Participants

In Experiment 2, we re-recruited participants, and we allowed previous participants to participate again. A total of 25 participants took part. 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.

### 5.3 Results

Due to the non-normal distribution of the data, we used the Wilcoxon signed-rank test for comparisons. Figure 4 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.

*5.3.1 Motion sickness slider maximum scores.* The maximum level of Motion Sickness 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 ($M = 2.05, SD = 1.70$).

*5.3.2 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 ($M = .92, SD = .89$).

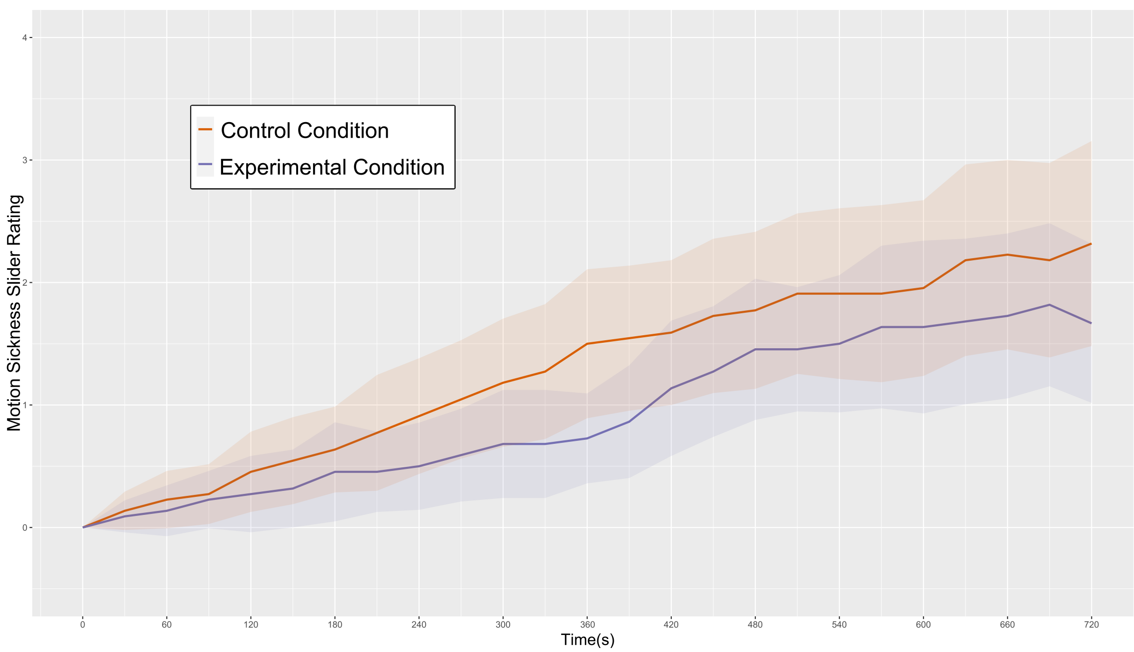


Fig. 4. Value of the real-time motion sickness slider for the two conditions. The shaded area represents the corresponding confidence interval.

*5.3.3 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 ($M = 20.38, SD = 14.21$).

*5.3.4 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 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 ($M = 27.03, SD = 27.94$).

*5.3.5 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 ($M = 96\%, SD = 3\%$).

*5.3.6 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 ($M = .52, SD = .12$).

## 6 OVERALL DISCUSSION

In Experiment 1, we found that our design, manipulating a planar 2D virtual display's motion as a visual cue to provide awareness of the user's physical motion, had a mitigating effect on motion sickness with a rotation coefficient of 0.3. In Experiment 2, we used a longer duration of experienced rotation, which induced a higher level of motion sickness symptoms, and a more controlled validation (one session per day). Under these more rigorous motion sickness conditions, we further demonstrated our cue design has a significant effect. The results demonstrate that our visual design had a significant effect on reducing motion sickness-related symptoms when setting the coefficient to 0.3.

In the maths task, we did not observe significant variations in participants' accuracy levels, thus, for productivity tasks such as this, performance was not reduced by our technique. For the second attention task, in both experiments, participants responded to the attention task within an average of 0.6 seconds, indicating that they maintained an upright posture and focused their attention on the task plane in VR. This ensures that the visual cues we designed consistently contributed to alleviating motion sickness in participants.

Our work builds upon previous research [17, 26, 42] that involved manipulating interfaces and content on 2D displays on a tablet to convey vehicle motion information, and extends them by demonstrating how such manipulations can be applied in a 3D context to planar content rendered in VR. Our experiment has demonstrated the effectiveness of delivering such implicit visual cues. In doing so, this opens up future research on how to implicitly convey motion cues, and expands our capability to interleave motion cues with planar content. Our research findings indicated that using a display rotation with a lesser degree could reduce motion sickness whilst still enabling participants to see and interact with a maths task presented in a 2D window. Our design is applicable to most common 2D planar interfaces rendered by an XR headset, contributing to the improvement of motion sickness in future autonomous vehicles and enhancing the experience of using VR/XR in self-driving cars. Our visual cue is based on manipulating the presentation of existing 2D planar content and does not require additional forms of visual information (e.g. cityscape [50], virtual particles [11] or other overt additional visual or multi-modal motion cues) so that it could be applied to many generic existing 2D content (movies, TV, 2D productivity apps like *Immersed* in VR/XR without requiring extensive additional work to accommodate the future demand for using XR devices in vehicles. This advantage opens the potential for an extensive range of existing VR applications to be optimized and integrated into vehicular systems, thereby profoundly enriching the user's travel experience.

## 7 LIMITATIONS AND FUTURE WORK

This paper represents our first step towards a new type of motion cue that can implicitly convey motion by manipulating planar display content presented in VR/XR. Our design 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 experiment was conducted using a rotating chair rather than in a real vehicle. The rotating chair can only simulate yaw rotation. In a real vehicle, yaw, pitch, roll, and linear motion are all present. We could not test our solution for linear motion but propose that the 2D plane would move towards/away from the user for acceleration/deceleration. We are in the process of planning an experiment founded on a real-world vehicular platform [37], aiming to substantiate the applicability of our design in practical scenarios. With the vast potential for content display in VR devices, we can recreate and incorporate designs like *MotionReader* [17] to work in tandem with our rotational motion cue designs. Ultimately, we plan establish effective implicit cues for all kinds of motion, then combine and implement our design in actual vehicles to better validate its ecological validity.

Additionally, we subjected participants to motion that was representative of the turns of a car on a road route, but this type of motion may not fully be representative of the movements that people may experience in real vehicles as the city road network consists of various road environments [54], which could potentially lead to more severe symptoms of motion sickness. And for ethical reasons, we screened out participants who were likely to be particularly susceptible. Thus our experiment was likely to only induce in general mild motion sickness. To overcome this limitation in future experiments, longer exposure times or more frequent rotations may be employed. Also, due to the relatively low difficulty level of the maths task, the accuracy rate was excessively high. We speculate 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, there are a variety of tasks have been employed in motion sickness research (e.g. reading [50], attention[28]). Future research should consider the suitability and validity of different primary tasks in replicating the cognitive demand expected during typical passenger activities. Furthermore, we look forward to comparing the performance of our method for implicitly conveying motion with other explicit visual motion cues and exploring the Pros, Cons, and Trade-Offs between implicit and explicit conveyance of motion.

## 8 CONCLUSION

This paper shows that we can implicitly convey motion cues through manipulating the orientation of planar content rendered by an XR device to significantly reduce motion sickness. This opens up further research into implicit rather than explicit visual motion cues that could be less visually obtrusive than existing cues. Also, our paper extends a growing body of research on implicitly conveying motion through manipulating the presented content alone [17, 26, 42], for the first time by manipulating 2D planar content as presented on an XR headset. Through experiments on a simulated motion platform, we have demonstrated that such a design can significantly alleviate motion sickness. It suggests that manipulating the planar display content can be implemented in XR environments and contribute to alleviating motion sickness. Such environment provides a more realistic and immersion simulation for these technologies and helps us find more tools to convey motion cues.

Through our visual display design reducing motion sickness, the use of VR devices in vehicles will become an indispensable part of travel, transforming the car, plane, bus or train experience for passengers into an infinite virtual space, ultimately improving the overall passenger experience.

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