Augmenting Virtual Spatial UIs with Physics- and Direction-Based Visual Motion Cues to Non-Disruptively Mitigate Motion Sickness

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Abstract

The use of Virtual Reality (VR) technology in moving platforms such as vehicles can be difficult due to significant issues around motion sickness, partly due to the physical motion being occluded in VR. The use of visual cues within VR can mitigate this motion sickness. However, these additional visual cues can disrupt users. This paper presents two studies conducted on a yaw-motion platform, investigating the effectiveness of our efforts to manipulate the visually perceived motion of spatial UIs within VR environments using novel physics-based cues, reducing motion sickness with less distraction on tasks. The first study validates our design's effectiveness, while the second compares it with existing solutions (speed/direction-base cues) regarding motion sickness and distraction levels among VR users. Our findings show that our design can relieve rotational motion sickness while concurrently diminishing distraction. This study serves as a valuable starting point for research into non-disruptively interleaving motion cues with spatial UI components within VR environments to mitigate motion sickness, emphasizing the delicate equilibrium between motion sickness mitigation and preserving the user experience.

CCS Concepts

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

Keywords

Virtual Reality, Motion sickness, VR Spatial UIs, Visual Cues

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1 Introduction

Cutting-edge spatial computing platforms [1] like Virtual Reality (VR) devices such as Meta Quest 3 and Apple Vision Pro, have the potential to revolutionize our interaction with digital content, thereby significantly enhancing the user experience. These technologies enable the presentation of virtual displays that facilitate engagement with content in ways that go beyond the capabilities of existing displays, such as watching 3D movies, multi-desktop productivity, or browsing the web [24, 26]. Virtual displays are fully customizable in terms of size and position in three-dimensional space, including depth, catering to individual user preferences and comfort levels. This innovative approach holds the promise of not only making passenger travel experiences more enjoyable but also optimizing them from an ergonomic perspective [24].

However, motion sickness remains a significant challenge when using VR, especially on moving platforms, for example during travel [7, 34] as well as gaming simulators [33]. This challenge impacts the overall comfort of user during their journeys and potentially hinders the realization of innovative VR experiences. The prevailing theory posits that motion sickness is primarily caused by a sensory conflict between expected and experienced vestibular and visual self-motion [37]. When users are in motion, their vestibular system receives information related to the physical movement, while their visual system receives conflicting information - such as the static interior of the vehicle or motion simulator; or the static virtual or real displays being viewed in these moving environments that both occlude any perception of motion, and may also provide incongruent cues themselves (e.g. vection cues from an action movie). The use of VR headsets can further contribute to this conflict by completely occluding the outside visual world. However, with thoughtful design, VR headsets also hold substantial promise as tools to mitigate motion sickness [33, 35]. By implementing strategies rooted in sensory conflict theory [20, 28], they can provide visual stimuli that align with the vestibular system's perceptions to reduce the occurrence of motion sickness.

Research findings indicate that the use of additional visual cues in VR, which align with users' perceived self-motion, can effectively delay the onset of motion sickness [3, 33]. This approach involves providing visual motion cues that mimic the visual signals users would experience. Nevertheless, the question of how best to non-disruptively convey the physical motion of the user in VR to reduce motion sickness remains unclear. It has been demonstrated that additional visual motion cues can be effective, as indicated by various studies [4, 5, 19, 21, 25, 29, 30]. However, this approach has the potential to compromise the overall user experience by diminishing immersion and causing distractions [25, 31, 42]. This counteracts efforts in VR to enhance the user experience. On the other hand, in the absence of these additional visual cues, motion sickness could greatly hinder individuals from enjoying their travel/gaming simulator experience and risk rejection of using VR. This dilemma underscores the importance of developing innovative visual cues that strike a delicate balance between mitigating motion sickness and maintaining a satisfactory user experience.

Hence, our research sets out to investigate how best to incorporate visual motion cues into existing VR spatial content whilst minimizing distraction to the primary task. We propose that we can convey motion more abstractly, with implicit *Physics-Based Cues* (PBC) conveying motion by the movement of contents in VR spatially. For example, augmenting the spatial UIs with the movement of swinging virtual items, such as hanging ornaments in a virtual room or fuzzy dice that can be found in virtual car interiors. Therefore, we devised a PBC that simulates the physical movement of a hanging red ball to convey motion information in VR spatial implicitly. Our visual cues in the VR spatial interact in accordance with the motion of the platform the user is on. Such PBCs can seamlessly blend into realistic virtual reality spatial environments, reducing distractions. We initially conducted a multi-session study utilizing a 1-degree-of-freedom (1DoF) rotating chair, subjecting participants to the same motion profile. Our investigation compared our PBC against no visual cue to corroborate the efficacy of our design in mitigating motion sickness.

After demonstrating the effectiveness of our PBCs, we identified two additional representative motion sickness mitigation designs to compare. We conducted another multi-session study using the same rotating chair to analyze the performance of these three designs in terms of mitigation and user distraction. Regarding the first design, we incorporated the cues employed by Pöhlmann *et al.* [33]. This approach entails replacing the entire VR background with a cityscape (or other realistic environment) and conveying motion information through the rotation of the entire background. This approach fully occupies the background in the VR scene and explicitly communicates the speed and direction of external motion, together with the degree of rotation, direction of rotation, and optic flow to completely match physical motion. This condition uses matched motion design and is a widely adopted and demonstrated effective visual cue. This condition will be referred to as the *Speed-and-Direction-Based Cue* (SDBC) from now on. 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, we also tested an explicit *Direction-Based Cue* (DBC), previously shown to be effective in anticipatory motion cue research. This cue was based of the work by Karjanto *et al.* [19] and incorporated yellow arrows within the VR environment to make the motion information more prominent and easily noticeable enhancing participants' situational awareness.

We compared the effects of these different designs on motion sickness mitigation from potentially high information density (speed-and-direction-based cue) to lower density (physics-based and direction-based cues), to understand the trade-off between reducing motion sickness and the potential for causing distraction. Our experimental results affirm that both the speed-and-direction-based cue as well as the physics-based cue successfully mitigated motion sickness. Notably, our design incorporating physics-based cues achieved this mitigation with significantly less perceived distraction. By demonstrating the potential of manipulating spatial interfaces based on physical movement to implicitly address motion sickness in mitigating motion sickness while keeping distraction low, we raise questions about what kinds of visual perception of motion in VR environments can resolve sensory conflict (beyond optic flow based cues), and open the door to a range of new ways by which self-motion can be non-disruptively integrated into VR experiences, ultimately aiming to support user experience.

2 Related Work

2.1 Motion Sickness When Using VR

Motion sickness is a state of discomfort characterised by symptoms such as headaches, nausea, dizziness, and, in extreme cases, vomiting [22]. It is widely acknowledged that motion sickness is determined by three principal elements: the nature of the stimulus provoking the sickness, the personal susceptibility of the individual to such stimuli, and the duration for which the individual is exposed to these stimuli [37]. The most accepted explanation for the occurrence of motion sickness is the sensory conflict theory [27, 36, 38]. This theory posits that the human vestibular system comprises otolith organs and semicircular canals, which are utilized for the perception of gravity as well as horizontal and vertical rotation [18]. When the information sensed by the vestibular system does not match what the eyes see, it can lead to motion sickness. However, this theory does not explain individual differences very well.

When users are on a moving platform, such as a driving simulator, vehicle, or rotating platform, their vestibular system receives information about their passive self-motion while they might be focused on other activities that lead to their visual system primarily receiving stationary/conflict self-motion cues. Hence, the anticipated use of VR brings with it obstacles. The discomfort caused by motion sickness is not only immediate but can also have prolonged effects, lasting several hours beyond its onset. This can significantly compromise the comfort of the user's journey, undermining the potential for productive use of travel time [8]. In future autonomous vehicles, the occurrence of motion sickness is anticipated to rise. This increase is partly due to individuals transitioning from drivers to passengers that are likely to engage more often in Non-Driving Related Tasks (NDRTs) [7]. Passengers tend to experience motion sickness more frequently than drivers [39], attributed largely to their lack of control and diminished situational awareness. Therefore, in future using VR, it is crucial to address the challenges brought about by motion sickness.

2.2 Motion Sickness Mitigation using Visual Cues

Many research studies have concentrated on the sensory conflict theory and have created visual/multimodal cues that display optic flow patterns in VR that would have been perceived visually if the outside world had not been occluded. Past research has shown that incorporating these additional visual cues in VR, which align with users' physical perception of motion, can substantially reduce the incidence of motion sickness [4, 5, 19, 21, 25, 30, 33].

Various designs have used visual cues to alleviate motion sickness symptoms effectively. On the one hand, some studies have mapped motion information onto the VR environment in a direct and concrete manner. For instance, Hock *et al.* [15] map vehicle motion to the VR world as visual cues and such cues allow users to experience the movement within the VR experience. Similarly, Cho *et al.* [3] discovered that by adapting a virtual road to mimic the actual vehicle's movements, they could harmonize the virtual environment with the user's vestibular sensation, significantly decreasing the sensation of motion sickness. These attempts have proven that displaying simulated external motion as visual cues within the VR environment is an effective strategy. On the other hand, an expanding field of research has been investigating ways to integrate motion cues directly into the content being viewed. The goal is to convey information about movement in a way that is both abstract and subtle, enriching the user's experience by embedding these cues seamlessly into the narrative or visual presentation. Hanau and Popescu [14] developed the *MotionReader* to investigate the effectiveness of different visual cues on e-readers. They attempted to subtly convey acceleration by moving the virtual border of an e-reader against the direction of acceleration, and also using a spring ball's movements to convey the direction of external motion. This method aims to convey acceleration in an implicit way. They propose that exploring the potential of simulating this interaction through a virtual reality window could offer significant benefits. Qiu *et al.* [35] brought a similar design into the VR environment. Their findings showed that the rotation of planar 2D NDRTs content in the VR space itself can serve as a visual cue to alleviate motion sickness induced on a 1DoF motion platform. A similar effect can be achieved through multimodal cues, as described by Pöhlmann *et al.* [33]. They proposed that the combination of visual and auditory cues could not only mitigate motion sickness but also enrich the user experience, highlighting utilizing multiple cues to diminish the impact of motion sickness.

2.3 Distraction of Visual Cues in VR

Much of the public excitement around VR technology is centred on immersive VR that dramatically enhances user experience [2]. Since many VR NDRTs are based on 2D planar tasks (e.g. reading, watching movies, gaming), Garcia and Insung [11] suggest that attention in such type of 2D platform task is crucial. Although previous work has demonstrated that additional visual cues can be effective, as visual cues require quick eye movements for correct perception and processing [9], their introduction may disrupt users from their focus while using VR [23], or divert the user's attention away from the task at hand. In VR content, distraction can negatively impact user experience and even reduce efficiency. Such a situation can occur when we introduce additional visual cues as a solution for mitigating motion sickness [25]. These studies highlight the importance of balancing the reduction of motion sickness with the potential distraction to users when utilising visual cues to alleviate motion sickness. Therefore, our research begins by addressing this balance. We explore potential design strategies in the VR space for visual cues that can achieve this balance.

3 Study 1 - Efficacy of Physics-Based Cues

In the first study, we tested a physics-based cue (PBC condition) against a control condition (no visual cue) while VR users performed a maths task. The PBC condition utilized physics-based visual cues that are interpreted as resulting from physical self-motion, akin to what objects in VR scenarios commonly experience during spatial user interactions. The idea is that instead of conveying the absolute motion by extra visual cues, we could convey the forces being experienced visually in a familiar yet abstract way. The brain's cognition of the physical motion of commonly seen objects may provide insights into self-movement awareness and perception. We manipulate the swinging of a small ball within the VR space to achieve this effect. Such swaying can be seamlessly integrated into VR spatial UI designs, such as balloons in virtual amusement parks, fuzzy dice hanging from the roof of a virtual cockpit, or leaves dangling outside a virtual window. This integration is believed to help reduce the distractions caused by visual cues.

The research questions of Study 1 were:

- **RQ1**: Does a physics-based cue that conveys external motion reduce motion sickness?
- **RQ2**: Does the introduction of a physics-based cue distract users?

We created a set of three balls that swing according to the direction of external motion. When external motion is detected, the balls will sway in the direction opposite to the motion due to inertia. The faster the external motion, the greater the amplitude of the sway. Owing to the influence of inertia, the amplitude of the balls' sway will not exceed 90 degrees. Upon cessation of the external motion, the balls promptly revert to their initial positions. We positioned them behind the task to avoid obscuring the primary task interface. See 2. Our design subtly conveys information about the direction and speed of external motion through the pendulum movement of the balls. As a control, we utilized the same design as the PBC condition, but the balls were fixed in a stationary position, oriented vertically downwards.

3.1 Experimental Platform

We used a RotoVR (www.rotovr.com) rotational chair that offers 1 DoF rotation along the yaw-axis as our motion platform. This platform can effectively simulate rotational movements of various motion platforms including game simulators and vehicles [6]. Participants were seated on the chair whilst wearing a Meta Quest 2 headset, see Figure 1. We controlled the chair rotation speeds by three levels, 25 deg/second, 35 deg/second, and 45 deg/second [33]. Rotation speeds were classified as *easy* ($\approx$ 25 degrees per second), *medium* ($\approx$ 35 degrees per second), and *hard* ($\approx$ 45 degrees per second). Each condition was presented for 12 minutes on separate days to avoid cumulative motion sickness effects between conditions.

Figure 1: A participant engages in rotational movements while seated in the *RotoVR* rotational simulation chair.

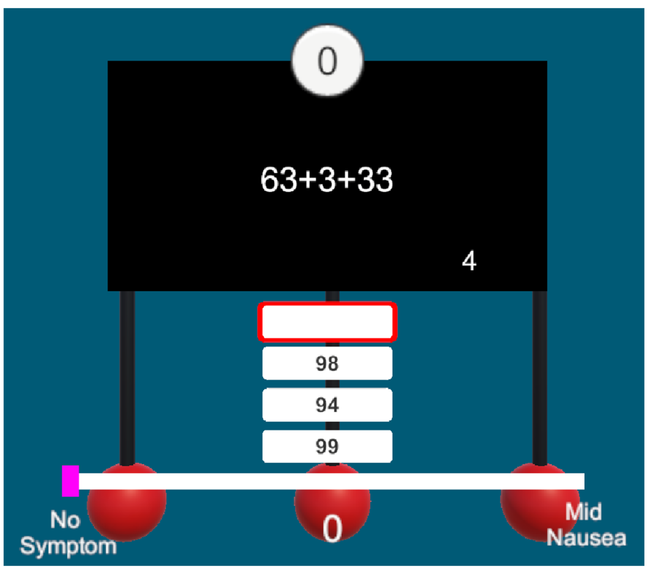

Figure 2: Participant's visual experience. The screen presents a three-number addition mathematics question(in the study 1, it was a two-digit addition) along with multi-choice answers and a slider for the participant to indicate their current level of motion sickness in real-time.

3.2 Measurements

3.2.1 Motion Sickness. The same measures were used in Studies 1 and 2. We employed two measures of motion sickness:

Simulator Sickness Questionnaire (SSQ, [21]). Before and after completing a condition of the experiment, participants completed the SSQ, resulting in an overall measure of motion sickness for each condition. SSQ has been extensively utilized to assess the severity of symptoms associated with motion sickness due to the absence of visual cues [30, 33];

Real-time 7-point scale motion sickness slider. This slider, sourced from [13], is displayed beneath the VR task for the entire duration of the experiment, see Figure2. 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 [13], 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.

3.2.2 Task Performance and Distraction. We employed mathematical questions involving two-digit addition as the primary task to simulate a productivity activity. Similar mathematical tasks have been used in previous research to assess participants' cognitive capabilities and workload capacity [35, 41]. Similar mathematical tasks can maintain participants' focus on completing tasks and simulating cognitive activities without introducing additional optical flow disturbances. Furthermore, following the approach outlined by Yan *et al.* [41], 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.

3.3 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 [12]. Prior to the start of the experiment, participants were asked to reconfirm their eligibility, ensuring they fully met the experimental criteria.

3.4 Experiment 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.

3.5 Results

We used a Wilcoxon signed-rank test for comparisons between the control condition and physics-based cues condition as the data were non-normal distribution.

3.5.1 Continuous Motion Sickness Measure. We utilised the maximum value of our continuous motion sickness measure to reflect the peak discomfort level experienced. The motion sickness level reported by participants differed significantly between the Control and PBC condition ($Z = -2.07, p = .038$), with participants experiencing stronger symptoms in the Control (Median = 2.00, IQR = 3.00) compared to the PBC condition (Median = 1.00, IQR = 2.25), see Figure 3. The results also indicate that the experimental setup was effective in inducing motion sickness.

3.5.2 Total SSQ Scores. For brevity only the total SSQ (including Nausea, Oculomotor, and Disorientation) analysis is included here. Scores on the total SSQ differed significantly between the conditions($Z = -2.65, p = .044$), with participants scoring higher in the Control (Median = 91.93, IQR = 119.19) compared to the PBC condition(Median = 52.51, IQR = 79.77), see Figure 4.

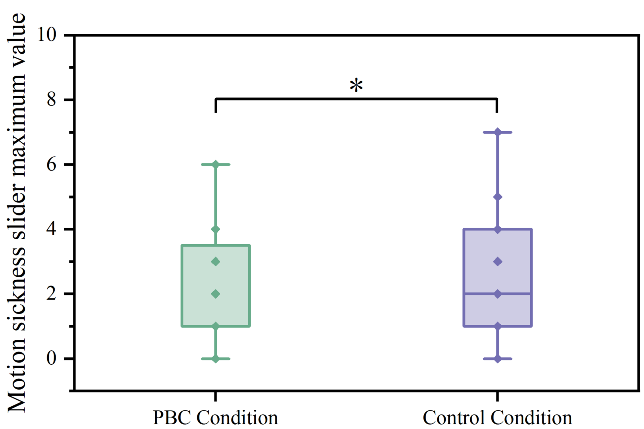

Figure 3: Motion sickness slider maximum scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.

3.5.3 Performance on the Maths Task. We analyzed accuracy in answering mathematical questions. No significant difference ($Z = -0.41, p = .679$) was found between the control condition (Median = 96%, IQR = 0.05) and the PBC condition (Median = 95%, IQR = 0.09).

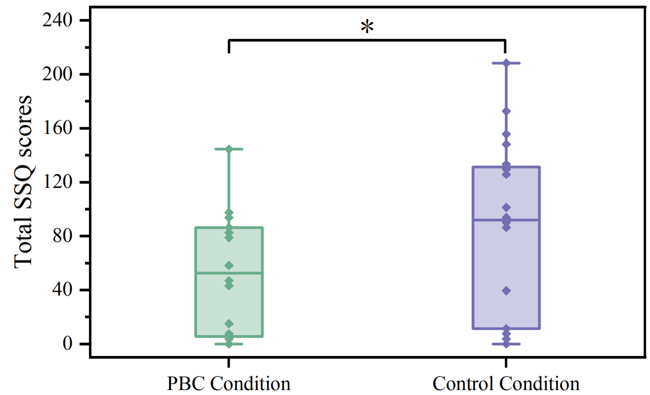

Figure 4: Total SSQ scores. The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.

3.6 Discussion

In Study 1, we devised a physics-based visual cue designed to match physical motion. The results answered our **RQ1** that our design could significantly alleviate symptoms of motion sickness, as evidenced by both the SSQ scores and the maximum values of the motion sickness slider. Regarding our **RQ2**, for the productivity performance tasks, we did not observe any significant differences in the accuracy of participants between conditions.

This study demonstrated that physics-based visual cues can convey external motion through the actual physical movement of existing elements within the VR scene. This does not explicitly display self-motion information, and if properly designed, it does not require additional elements (for example, movement forces could be applied to existing objects within the already existing VR scene), thereby UI design reducing the potential distraction to users.

This study led us to question how PBC design compared to commonly used visual motion sickness mitigation techniques that have been proven effective in reducing symptoms. To answer this question, further research and comparison between different types of cues are needed. This comparison could provide valuable insights into the efficacy of various visual cue designs in terms of mitigating motion sickness and their potential to disrupt the users' experience in a virtual environment. Therefore, Study 2 aims to answer this question by comparing our visual cue design with some existing, validated visual cues.

4 Study 2 - Comparing Physics-Based Cues with Others

Upon demonstrating the effectiveness of physics-based cues in Study 1, we identified two additional representative motion sickness mitigation designs using the same rotating simulation chair to analyze the performance of these three designs in terms of mitigation and user distraction. The research questions of Study 2 were:

- **RQ3**: Are there performance differences in mitigating motion sickness among the three different types of visual cues?

- **RQ4**: Do the three different types of visual cues have an impact on productivity task performance?
- **RQ5**: Do the three different types of visual cues differ in their impact on user distraction?

4.1 Study 2 Design

The study employed a within-subjects experimental design, with motion sickness and productivity measures as dependent variables. During the period of Study 1, we observed a high accuracy rate in the two-digit addition task, therefore to elevate the difficulty level while maintaining the graded difficulty of these mathematical tasks, for our Study 2, we introduced an additional digit to the original two-digit addition. The third digit was determined by calculating the integer average of the sum of the first two digits. Figure 2 shows the design of our tasks.

We also added an additional measure for distraction by designing a ranking question. The question subjectively evaluated the degree of distraction caused by the different motion sickness mitigation designs. Participants were instructed to rank the visual cues from the lowest to the highest distraction. The experiment comprised the same physics-based cues condition taken from Study 1 and the following two experimental conditions, with these conditions being presented in a counterbalanced order to mitigate potential ordering or learning effects:

4.1.1 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.* [19], where they alleviated motion sickness by displaying the anticipatory direction of upcoming motion. We integrated their design into the VR display, enhancing the visibility of the arrows by changing their colour to yellow. This was based on previous research findings that demonstrated yellow turn signals resulted in significantly shorter reaction times and are widely used in real cars [17], ensuring that they are more conspicuous and less prone to being missed. Since our other cues were not anticipatory, we presented our cues at the same time 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 virtual space as a visual cue. We explore whether the performance of such visual cues, which convey less information, is effective in terms of motion sickness mitigation. Since the arrows only convey information about directions of motion, we called these Direction-based cues (DBC). The left panel of Figure 5 illustrates this design.

4.1.2 SDBC condition: Speed-and-direction-based cues. This condition incorporates visual cues that simultaneously encompass both speed and direction of motion. We adopted the design introduced by Pöhlmann *et al.* [32, 33] that used a cityscape view as the VR background. Motion information was conveyed through the rotation of the background. This design uses the entire background in VR spatial as additional display content, aligning the speed and direction information from the background with external motion. Whenever an external rotation is detected, the entire virtual background (city scape) responds with an opposite rotation, presenting optic flow with speed and direction corresponding to the visual motion that would be experienced if participants were not wearing the VR headset experiencing the rotations. Pöhlmann *et al.*'s [32, 33] experiments have demonstrated the effectiveness of such a design in mitigating motion sickness, as depicted in the right panel of Figure 5. However, the large amount of visual motion that occurs in VR has the potential to be distracting from a primary task. This design represents the current "standard" mitigation strategy [5, 31, 33, 40], and we compare our design with these standard cues, which contain speed and direction information.

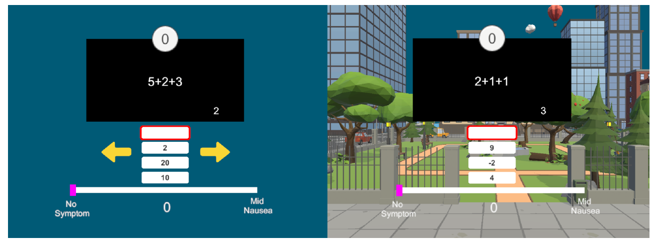

Figure 5: On the left is the experimental design for the Direction-based cue condition. On the right is the design for the Speed-and-direction-based cue. Motion information is conveyed through the rotation of the background.

4.2 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 [33]. Hence, 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 MSSQ [12] in advance of the study.

4.3 Experiment Procedure

The experiment 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.

4.4 Results

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

4.4.1 Continuous motion sickness measure. We compiled and plotted the development of the motion sickness slider ratings over time for the three conditions; see Figure6. We utilised the maximum value of our continuous motion sickness measure to reflect the peak discomfort level experienced. Results differed significantly between the conditions, see Figure6, $\chi^2(2) = 9.81$, 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, $Cohen'sd = 0.59$). 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).

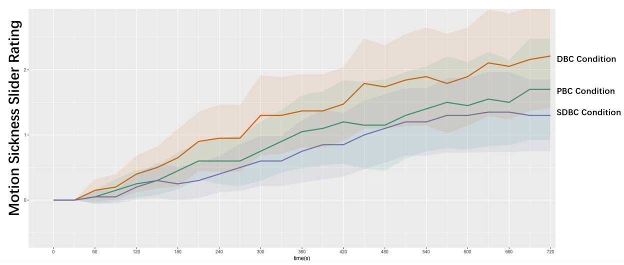

Figure 6: Development of motion sickness over time for the three conditions rated via the slider displayed in the headset. Shaded areas represent 90% confidence intervals. Y-axis represents Motion Sickness Slider values; participants were able to rate their level of motion sickness: 0: "no problems",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

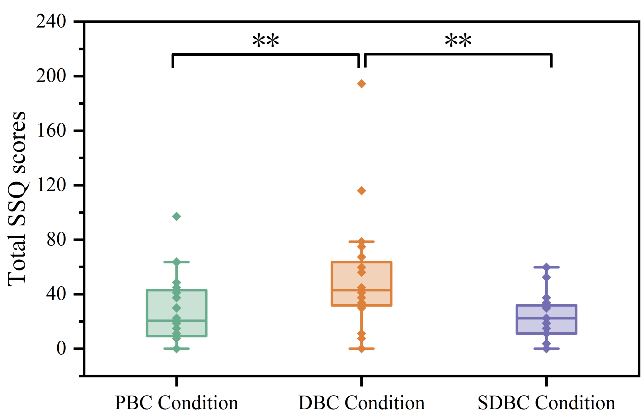

Figure 7: Total SSQ scores of study 2, The box in this boxplot represents the data's interquartile range, and the line inside the box denotes the median.

4.4.2 Total SSQ scores. Total SSQ scores differed significantly between the conditions, $\chi^2(2) = 15.38$, p < .001, see Figure7. *Post hoc* tests revealed a significantly higher level of motion sickness in the DBC condition (M = 52.17, SD = 43.33) than the SDBC condition (M = 24.31, SD = 17.09, p = .005, $Cohen'sd = 0.85$) and PBC condition (M = 27.33, SD = 24.45, $p = .002$, $Cohen'sd = 0.71$). 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).

4.4.3 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.

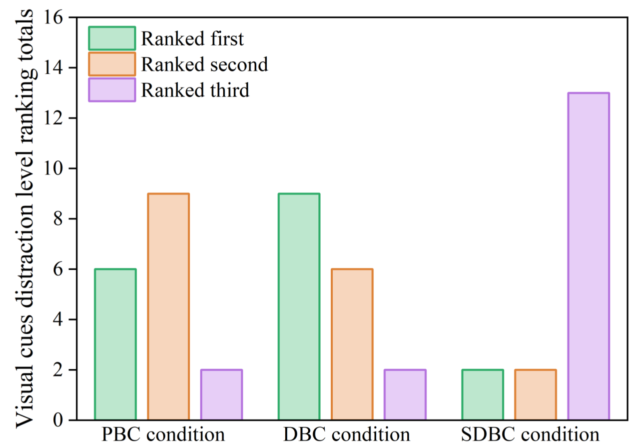

Figure 8: Distraction level rankings. We calculated the total rank sum for each condition, where ranking first means that participants considered that condition to have the highest distraction level.

In rankings of the distraction level of the motion sickness mitigation designs, 17 individuals were included in the final analysis, as 3 participants' responses were missing. We assigned values of 1, 2, and 3 to the participant rankings. A lower assigned value indicated a lower level of distraction. A Friedman test revealed a significant difference in rankings across the three conditions, $\chi^2(2) = 10.94$, p = .004, see Figure 8. *Post hoc* indicated that conditions PBC (M = 1.77, SD = 0.66p = .030) and DBC (M = 1.59, SD = 0.71p = .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).

4.5 Discussion

Study 1 showed that our physics-bases cues reduced motion sickness, hence in Study 2, we compared them with the 'standard' mitigation techniques of direction cues and speed-and-direction cues, to compare mitigation levels and to identify effects on task performance and distraction. Speed-and-direction cues, also called 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 answered our **RQ3**. 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.

For the maths task, representing productivity applications in VR interaction, we did not find a significant difference in accuracy rates among the three conditions, suggesting that in our **RQ4**, the different visual designs did not affect task performance. Regarding the **RQ5**, the ranking of distraction levels for visual cues, 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 demonstrated the best motion sickness mitigation performance in the experiment, they also introduced the highest level of distraction, suggesting that our physics-based cues provide a good compromise, with lower distraction and strong mitigation performance.

5 Limitations

There are some limitations to our 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. We are planning to use a platform with more degrees of motion to validate the ecological validity of our design for passengers specifically in the future. Additionally, our 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. We intend to utilise more objective methods, such as eye-tracking technology, to investigate this more effectively in the future.

6 Overall Discussion

6.1 Efficacy of Physics-based Cues in Motion Sickness Mitigation

Through two experiments, we validated that the mitigating effects of our novel physics-based cue on motion sickness are significant. Integrating the results of both experiments, we can observe that purely directional information was not as effective, but physical cues appeared to provide sufficient information to result in mitigation effects similar to those of speed-and-direction-based cues, which offer complete information about motion and show full optic flow outside of the VR headsets. While speed-and-direction-based cues have been extensively validated and implemented in previous research [16, 31, 33], our cues based on physical characteristics have proven effective for the first time. Such cues, if well designed, do not need to dominate the entire VR background or occupy all spatial dimensions of the VR environment. Instead, they can discreetly convey motion information while integrating seamlessly with the physical movements of the VR spatial UIs.

6.2 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 effect on the task. This could be attributed to the fact that the various visual cues may not have enough distraction to decrease participants' accuracy. Alternatively, it might be due to the fact that the tasks were not cognitively challenging enough, which resulted in generally 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 PBC and the DBC.

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. Our physics-based, PBC condition was designed to strike a balance between these two aspects. It approaches the effectiveness of widely used methods (such as the SDBC condition) while providing lower distraction, potentially creating a higher level of user comfort.

Furthermore, in demonstrating that physics-based motion cues can be effective, this opens the door to a breadth of new visual cue designs not based on typical matched motion-style visual conveyances of motion that could be better integrated into the VR environment and potentially manipulate spatial UIs already in the VR scene. Examples include the swaying of water on a table in response to movement when the user is situated in a virtual productive environment or the movement of tree and plant leaves in a jungle environment in reaction to the motion. Such approaches do not need to add any additional virtual objects and strike a balance, ultimately enhancing the user experience.

Finally, when we consider the prevailing theory of sensory conflict resulting in motion sickness, this work provokes new consideration of what constitutes appropriate visual stimulii 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 [10] 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.

7 Conclusion

In this paper, we introduce physics-based motion sickness mitigation cues, inspired by the movement of items in existing VR spatial UIs. These visual cues are designed to convey motion information within VR environments when used on motion platforms, effectively integrating with the dynamics of VR interactions. We first conducted a within-subjects experiment that demonstrated the effectiveness of the cues. Subsequently, we investigated the impact of these physics-based cues alongside two other distinct cue types (direction, and speed-and-direction cues) on mitigating motion sickness and their level of user distraction. We conducted our experiments in a controlled laboratory setting, where participants wore VR headsets and experienced yaw rotations induced by a rotating chair. Our results show that both physics-based and speed-and-direction-based cues significantly mitigated the occurrence of motion sickness. Furthermore, we compared the distraction of these three visual cues to user distraction. While speed-and-direction-based cue performed best in reducing motion sickness, they also caused the greatest distraction. Our physics-based cue reduced motion sickness but without being as distracting, suggesting they are an effective solution to both problems.

These results open up the discussion on the trade-off between motion sickness alleviation and user distraction for the first time. Through our design, we have integrated our visual cues into VR spatial UIs, representing an initial attempt to realize this direction. The significant potential of VR for enhancing immersion is one of the reasons for choosing VR. However, the introduction of invasive motion cues can lead to distraction, and the loss of immersion. We emphasize the importance of progressing towards minimally distracting motion cues to enhance the overall user experience. Through these carefully considered designs aimed at reducing motion sickness, the integration of VR devices into moving platforms such as simulators and vehicles will become an essential aspect of future VR design. This integration significantly enhances user experiences in flight simulators, driving simulators, and vehicles by transforming the real world into an immersive virtual space, ultimately enhancing the overall user experience.

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