# 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

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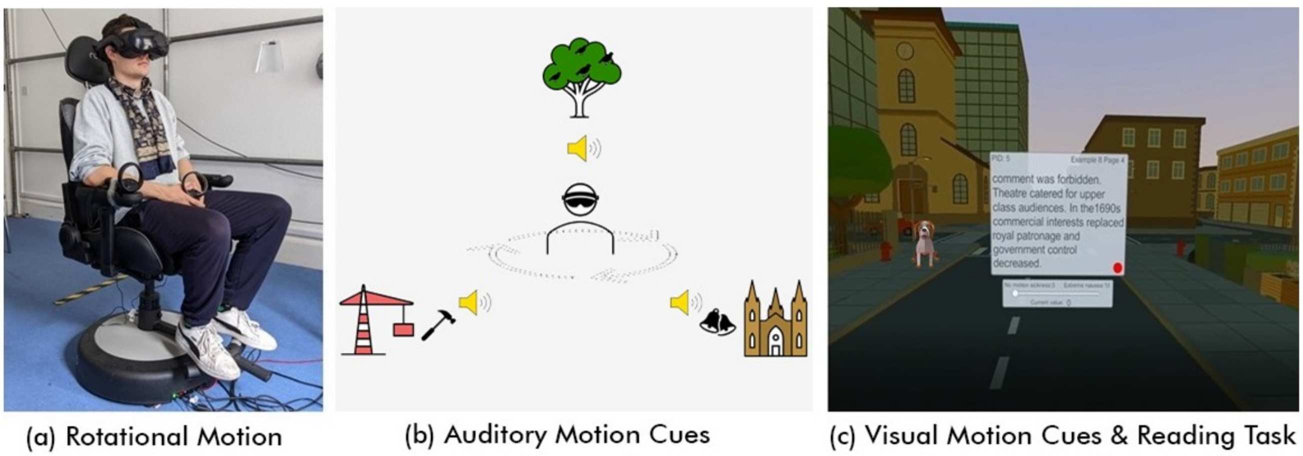


**Figure 1: (a) RotoVR chair and experiment setup, (b) Schematic representation of the auditory soundscape including the three landscape sounds, chosen based on visual landmarks in the virtual scene: church bells, bird chirping and construction noise, (c) Example of the virtual environment including the reading task, attention task and motion sickness scale.**

## ABSTRACT

Motion sickness is a problem for many in everyday travel and will become more prevalent with the rise of automated vehicles. Virtual Reality (VR) headsets have shown significant promise in-transit, enabling passengers to engage in immersive entertainment and productivity experiences. In a controlled multi-session motion sickness study using an actuated rotating chair, we examine the potential of multi-sensory visual and auditory motion cues, presented during a VR reading task, for mitigating motion sickness. We found that visual cues are most efficient in reducing symptoms, with auditory cues showing some beneficial effects when combined with the visual. Motion sickness had negative effects on presence as well as task performance, and despite the cognitive demand and multi-sensory cues, motion sickness still reached problematic levels. Our work emphasises the need for effective mitigations and the design of stronger multi-sensory motion cues if VR is to fulfil its potential for passengers.


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## CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**.

## KEYWORDS

motion sickness; virtual reality; rotation; automated vehicles

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# 1 INTRODUCTION

People spend large amounts of time travelling using private and public transport, with one main contributor being their commute to and from work. The average UK daily commute in 2018 was 59 minutes [31] and is rising over time. Such journeys are often perceived as repetitive and time wasting [32]. This time could be spent more productively by travellers for work, or for entertainment activities, such as watching a movie, reading or playing games. Research suggests that people want to spend their time productively when travelling in automated vehicles [63], such productivity tasks will largely rely on reading, with individuals working on virtual displays reading their emails, articles or browsing the internet. The benefit of Virtual Reality (VR) to such tasks is that it can transfer you into a virtual environment that is more suitable for work [64, 75].

However, many people get sick when engaging in such tasks while travelling, negatively impacting their journey. Once experienced, symptoms can persist for hours post-journey, meaning it is crucial that motion sickness onset be avoided where possible. The primary cause of motion sickness is believed to be the mismatch between sensory systems giving information about the self-motion of the passenger [89, 90]. When travelling in a vehicle, the vestibular system receives information about passive self-motion while the visual system often does not receive matching information. Passengers mainly view the interior of the car or focus their visual attention towards a phone or book, perceiving stationary visual cues, resulting in motion sickness [26].

Motion sickness is a key limiting factor when using immersive (and other) media when travelling. This problem is expected to grow with the arrival of automated vehicles [19, 23, 25, 26, 28, 43, 101]. This automation will turn drivers into passengers who may then use their time for non-driving related tasks (working, reading, watching movies, etc.). However, engagement in such tasks is also likely to increase the occurrence of motion sickness symptoms. Automated cars are also expected to come with a redesign of the interior to better fit the needs of passengers such as making the windows into screens, which may occlude the view of the external world, adding to the induction of motion sickness.

VR Head Mounted Displays (HMDs) have the unique possibility to serve both as a means of supporting new immersive transit experiences, and acting as a platform for delivering motion sickness mitigation. For the former, VR can act as a tool for entertainment or productivity, presenting virtual displays beyond what could normally be accommodated in the vehicle interior [68, 75, 79]. VR can also help passengers escape the perception of their confined physical space, immersing users completely into alternate virtual worlds [40, 68–71].

VR also shows significant promise as a tool for resolving motion sickness. Mitigation strategies based on the conflict between the sensory systems often utilise a breadth of approaches for visually presenting motion stimuli that are in line with the vestibular motion perceived by the passenger, reducing or postponing the onset of motion sickness symptoms [14, 15, 46, 58, 70]. However, not all research has found that presenting congruent visual motion stimuli can mitigate motion sickness experienced in moving vehicles [20]. This discrepancy in findings could be due to differences in the visual stimuli design, e.g. their location both relative to the car, and within the visual field of the passenger, or due to mitigating effects of attentional and cognitive demands of tasks performed while travelling [10, 129]. This highlights the need to identify suitable visual motion stimuli as well as suitable methods of presentation for them.

In this paper, we examine the potential of multi-sensory visual and auditory motion cues, presented alongside a VR reading task (a key component of productivity and entertainment activities) for mitigating motion sickness. Reading was chosen as a cognitive task here due to its high ecological validity[63]. In practice, people will use displays presented around them in the virtual environment to perform various work related task, such as reading their emails, the news, working on documents or browsing the internet. Reading in VR rather than on a tablet or book can also help enforce postural stability in the reader by positioning the virtual display ergonomically in front. This can have additional beneficial effects on passenger comfort.

We performed a multi-session study (4 sessions per participant) using an actuated rotating chair, exposing all participants to the same motion profiles. We tested experimental conditions in separate sessions to avoid cumulative effects of motion sickness, using an ecologically valid and cognitively demanding reading task while exposing participants to controlled visual and auditory stimuli in separate and combined conditions. These are all weak points of prior research, which often run multiple conditions on the same day [14, 15] or have less controlled motion profiles with vehicles driven on city roads [15, 70].

We theorise that effective vection (the sensation of visually induced self-motion) cues will prove similarly effective in reducing sensory conflict, and the resulting onset and experience of motion sickness, during real motion. Consequently, our visual and auditory motion stimuli were designed based on the strongest cues available in the vection literature, including both low level sensory information about self-motion as well as semantic information (see Figure 1). Stimuli containing semantic information [95, 106], placed in the background [77, 105] and periphery [12, 86] have been shown to be most efficient in eliciting vection. These stimuli should therefore be the most efficient in eliminating the conflict between the perceived sensory conflict and hence motion sickness. A visual stimulus covering large parts of the visual field could, however, be perceived as distracting from a primary activity, in our case reading [88], which is why we introduce additional auditory motion stimuli as a potential mitigation.

This is the first study to investigate the effects of auditory motion cues on the perception of motion sickness induced by physical rotation. Auditory motion cues on their own can elicit a sensation of self-motion [29, 44, 62, 92, 100, 119–121] and can enhance visually induced vection when combined [51, 93, 94, 97, 104, 115, 119]. 3D spatial auditory cues have, however, not yet been examined (alone or in conjunction with visual cues) when applied to conveying a real sensation of self-motion as would be experienced by a passenger in a moving vehicle. Auditory cues are expected to be less distracting from the primary reading task which, if they can contribute to mitigating motion sickness, makes them the ideal cue to integrate into a visual productivity task.

Our work is the first to combine visual and auditory motion cues to mitigate motion sickness induced by physical motion. It is also the first that evaluates the effects of such motion sickness mitigation strategies on the experience of presence as well as performance on a reading comprehension task in a virtual environment. This research provides insight for a future in which VR headsets will serve a dual function for travel: acting both as a tool to mitigate motion sickness as well as a platform for immersive productivity and entertainment.

### 1.1 Contributions

Our paper presents a user study investigating the effects of adding visual and auditory cues that are consistent with passively experienced rotational motion. We contribute the results of a multi-session (N=19, 76 sessions, 43 hours) motion sickness study examining the impact of multi-sensory visual, auditory and visual+auditory motion cues on motion sickness, presence, and task performance during an ecologically valid productivity-oriented reading task. This study is unique in bringing together research outcomes around multi-sensory vection cues and examining their efficacy under rotational motion. Our key findings are:

(1) Visual motion cues that are consistent with passively experienced vestibular motion can reduce motion sickness while conducting a productivity task in VR;
(2) Auditory motion cues have some beneficial effects on motion sickness when combined with visual cues;
(3) The addition of visual and auditory cues had no negative effects on perceived workload or task performance;
(4) Motion sickness has a negative effect on the experience of presence in VR and task performance - extending the results of prior work to a new domain (reading/productivity).

Through these findings, we further our understanding regarding the need for, and design of, effective multi-sensory motion sickness mitigations when engaging in productivity tasks. We also validate that effective vection cues from the literature can be utilized as motion cues for resolving sensory mis-match to an extent, opening up promising new research directions in multimodal motion cue design.

## 2 RELATED WORK

### 2.1 VR for Travel and Motion Sickness

People spend large amounts time travelling and commuting to and from work, with the average commute time steadily increasing [31]. To spend this time productively, many commuters engage in non-driving related tasks; they work using laptops, tablets or smartphones, reading books, playing games or watching movies on small displays. Using such displays can often lead to passengers tilting their head downwards (holding the display on their lap), with such a head position leading to increased motion sickness [27, 58]. VR allows us to overcome these restrictions and experience virtual displays of any size positioned ergonomically around oneself enforcing postural stability. Using VR headsets while travelling will enable passengers to use their travel time in new, productive and exciting ways. They can, for example, use large virtual displays to spend their time working [68, 69, 71, 75], can watch movies on large cinema like screens, or can engage in a 3D immersive games [72].

However, around one third of travellers suffer from motion sickness [57], and poor UI design may induce it in many more. Symptoms include: nausea, vomiting, dizziness, headaches and fatigue, with the primary cause of motion sickness believed to be a mismatch between self-motion information perceived from different sensory systems [89, 90]. This conflict is often enhanced when one engages in a non-driving related task, for example when reading a book, as almost no visual cues giving information about self-motion are perceived - which explains why we often feel sick when trying to read a book or use our phone in a moving car [19, 28].

### 2.2 Using Sensory Motion Cues to Mitigate Motion Sickness in Moving Vehicles

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 both research [14, 15, 46, 58, 70] as well as commercial applications, such as Holoride [2] to reduce motion sickness and improve game enjoyment. Large visual optic flow patterns can induce a sensation of illusory self-motion termed *vection* [33, 34, 42, 82], making the observer feel as if they are moving even though they are stationary. This illusion can be utilised for mitigating motion sickness in moving vehicles. When the visually presented motion pattern eliciting vection provides self-motion information that is congruent with the perceived physical motion, it should reduce the conflict between the visual and vestibular system and thereby reduce or eliminate motion sickness. This visual motion can be presented in the background independent of a productivity task or can be integrated into a game and build the foundation of the avatars locomotion in the game [41, 83, 126]. Vection literature has identified various stimulus attributes, such as speed, density and location, that can affect the sensation of vection. For a visual motion cue to be most effective in reducing motion sickness, we believe it should elicit a strong and convincing sensation of vection. We discuss the current literature on visually induced vection below and base our visual motion stimuli on this.

### 2.3 Vection Induced by Multi-Sensory Cues

Visual motion is not the only sensory cue that can elicit a sensation of vection; auditory and tactile cues can also be used [22, 55, 60, 94, 97, 99, 100, 117, 119, 120], with the sensation being enhanced if multiple sensory systems receive congruent self-motion information at the same time [6, 94, 97, 103, 104, 108]. For our study, we used visual and auditory vection cues presented both independently and in combination. Simultaneously presenting congruent visual and auditory motion cues results in a stronger sensation of vection compared to purely visual or auditory presentation [94, 104, 111, 115, 119, 120]. Auditory vection cues presented on their own generally elicit a weaker sensation compared to visual motion cues. They do, however, come with other advantages when using them for motion sickness mitigation. Independent of the visual display used or the visual task presented on such a display, the auditory vection cues can be presented omni-directionally, providing the passenger with information about turns, accelerations and decelerations. Auditory cues could also allow for better dual-task performance [123]. Most non-driving related activities are primarily vision-based (reading, watching movies, working, etc.). Auditory vection cues require separate mental resources allowing for parallel processing of their information without adding to visual demand. Visual motion stimuli presented in VR or on large screens also have the potential to induce VIMS (Visually Induced Motion Sickness [111]) on their own. Therefore, if the visual motion is not completely in line with the physically perceived motion, the stimuli could potentially add to motion sickness. Auditory cues have the potential to elicit vection without the risk of contributing to motion sickness [36, 50]. Ours is the first study to look at the effects of of auditory and combined visual and auditory vection cues giving self-motion information based on physical rotation on motion sickness.

## 2.4 How to Best Present Sensory Cues to Mitigate Motion Sickness

*2.4.1 Visually Induced Vection Literature.* The type of illusory self-motion experienced in our study is termed circular vection, self-rotation around the yaw axis. This experience is affected by multiple factors, such as the size of the motion pattern, with patterns covering more of the visual field eliciting stronger sensations of vection [7, 12, 73, 76, 77, 109, 116]; the exposure duration to the pattern, with prolonged exposure eliciting a stronger sensations of vection [107]; the speed of the moving pattern, with faster moving stimuli enhancing the sensation of vection [12, 22, 78, 91, 109, 114]; stimulus density of the pattern, with more complex and dense visual scenes resulting in a more compelling sensation of vection [9, 12, 22, 52, 91]; and the location of the pattern in the environment as well as visual field, with motion patterns perceived in the periphery and in the background resulting in stronger vection [12, 21, 42, 73, 76, 77, 81, 108, 109]. Scene perceptions and cognitive tasks also affect the sensation of vection [95]. Natural scenes elicit stronger vection than more abstract ones [91, 98]. When presented with stimuli containing the same low-level visual motion information, naturalistic scenes containing semantic information elicit a stronger sensation of vection compared to more abstract stimuli [98], the interpretation of a moving stimulus can affect the strength of the experienced self-motion. Moving visual stimuli that depict objects that are generally stationary such as houses, trees or mountains enhance the perception of vection, compared to objects that are not always experienced as stationary, such as cars, trains or animals. Abstract objects cause a weaker sensation of vection as we have no prior experience with them and have no knowledge about them being stationary or self-moving in nature.

*2.4.2 Auditory Induced Vection Literature.* Similar effects of semantic information have been found for auditory vection. Our prior experience with sounds as either being stationary or moving in nature can affect our sensation of vection. Sounds representing objects that in the real world do not move, such as church bells or house alarms ("acoustic landmarks") enhance the experience of vection compared to sounds that represent objects that can move, such as the siren of an ambulance or the sound of an ice cream van, or abstract sounds such as pink noise [29, 62, 93, 119–121]. We designed our visual and auditory vection cues based on these findings. Our visual motion cue comprised of a virtual city scene including various types of buildings (church, houses, cinema, construction site), streets and a park (see Figure 1 (c) and 2) and our auditory vection cues were based on three landmarks from the visual scene: church bells, construction noise and birds singing in the park (see Figure 1 (b)).

## 2.5 Multi-sensory cue Integration, Motion Sickness and Presence

Multi-sensory cue integration can additionally be beneficial as it increases the user's sense of presence and thereby often reduces their experience of adverse symptoms [16, 17, 39, 61, 62, 122]. Both motion sickness and vection are related to the experience of presence in VR, where presence can be defined as the illusion of being there [113, 127]. They, however, relate to presence in the opposite direction, enhancing the sensation of presence in VR is negatively associated with motion sickness (for a review see [122]), while experiencing a stronger sensation of vection during locomotion can enhance the sensation of presence [52, 95]. Similarly to vection, including information from multiple senses increases the sensation of presence [16, 17, 39, 61, 122]. This would suggest that when both congruent visual and auditory motion stimuli are included and a strong sensation of self-motion is experienced, not only should motion sickness be reduced but presence should be enhanced. Experiencing less motion sickness while performing our reading task should therefore result in a stronger sensation of presence.

## 2.6 Multi-sensory Cue Integration, Motion Sickness and Task Performance

As with presence, a reduction of motion sickness [18, 54, 66, 85, 110] as well as the combination of multi-sensory cues [16, 17, 61] shows positive effects on task performance. Previous work has investigated the effects of motion sickness on performance on various tasks such as navigation [54], n-back tasks [110], short term memory and working memory tasks [18, 85]. Results showed that motion sickness had negative effects on performance on all these tasks. No work so far has, however, investigated the effects of motion sickness on a reading comprehension task (a key component of productivity), making this the first study to investigate the possible positive effects multi-sensory cue integration could have on the reading experience of passengers in moving vehicles.

# 3 STUDY OVERVIEW

In this study, we examined the effects of visual and auditory motion cues on motion sickness elicited by physical yaw rotations, while VR users performed a reading task. We investigated the relationship between motion sickness, presence and task performance. The research questions were:

- Can visual (**RQ1**) or auditory (**RQ2**) vection cues that are congruent with experienced physical motion reduce motion sickness, and increase presence and task performance on a reading task?
- **RQ3**: Do congruent visual and auditory vection cues reduce motion sickness, and increase presence and task performance?
- **RQ4**: Is the addition of visual and auditory vection cues perceived as more mentally demanding?
- **RQ5**: Does the experience of motion sickness reduce presence and performance on a reading comprehension task


**Figure 2: Example of the visual landscape including the motion sickness scale (centre), reading task (left), reading comprehension questions (right) and attention task (red and green dot).**

## 3.1 Study Design and Setup

The study used a *within-subjects* design with motion sickness level, presence and task performance as dependent variables and condition (visual, auditory, and combined vection cues) as independent variables. The experiment consisted of five experimental conditions in which the participants were seated on a rotating chair,see Figure 1 (a), which rotated around the yaw axis. Participants performed a reading comprehension task as well a secondary attention task. Visual and auditory motion stimuli were varied dependent on the condition and their location was either locked on the yaw axis, hence not giving any motion cues that match the physical rotation perceived or were placed in the environment giving matching motion information. In conditions containing auditory cues locked to the yaw axis the sounds were always perceived as coming from the same direction in relation to the participant's position, for example the church bell sound was always perceived as coming from the left side and the construction sound as coming from behind them independent of the physical rotations perceived. When the visual cues were locked to the yaw axis the same part of the visual scene was always in front of the participants, for example they always see the park in front of them and the church to the right. While in the condition in which the visual and auditory cues where placed in the environment the spatial sounds and the visual scene were perceived in line with the rotation of the chair. The baseline condition *C1-NR*, which did not contain any physical motion (chair rotation) was always presented first, with the other 4 conditions being presented in counterbalanced order to avoid ordering or learning effects.:

**(*C1-NR*) Baseline with no chair rotation**: In this condition the chair was stationary and participants experienced no physical motion. The auditory and visual feedback was also present here. *No conflict between visual, auditory and vestibular motion.*

**(*C2-A*) Auditory motion cues without visual motion cues**: In this condition the chair was rotating with participants experiencing physical motion. The visual scene around the participant was locked to the yaw axis, thereby not giving any information about physical self-motion. The spatial auditory cues were placed around the participant providing information about their self-rotation. *Conflict between perceived visual and vestibular motion. No conflict between perceived auditory and vestibular motion.*

**(*C3-V*) Visual motion cues without auditory motion cues**: In this condition the chair was rotating with participants experiencing physical motion. The visual scene around the participant was placed in the environment, providing congruent information about physical self-motion. The spatial auditory cues were locked to the yaw axis, therefore not providing information about self-rotation. *No conflict between perceived visual and vestibular motion. Conflict between perceived auditory and vestibular motion.*

**(*C4-AV*) Visual and auditory motion cues combined**: In this condition the chair was rotating with participants experiencing physical motion. The visual scene around the participant was placed in the environment, providing congruent information about physical self-motion. The spatial auditory cues were placed around the participant providing information about their self-rotation. *No conflict between perceived visual and vestibular motion. No conflict between perceived auditory and vestibular motion.*

**(*C5-NC*) Baseline with chair rotation and no matching visual or auditory motion cues**: In this condition the chair was rotating with participants experiencing physical motion. The visual scene around the participant was locked to the yaw axis, thereby not giving any information about physical self-motion. The spatial auditory cues were locked to the yaw axis, therefore not providing information about self-rotation. *Conflict between perceived visual and vestibular motion. Conflict between perceived auditory and vestibular motion.*

The virtual environment consisted of a Unity city scene (see Figure 1 (c)) including: a church, a cinema, houses, as well as a park, roads, cars and a construction site. Depending on the condition, this virtual scene rotated around the user based on the chair rotation or was locked to the yaw axis, resulting in them viewing the same part of the scene in the background throughout the entire condition. One of the VR controllers was attached to the rotating chair (see Figure 1 (a)) and its position was used to lock the virtual reading display to be in front of participants and in the condition excluding visual vection cues to lock the scene to the chair. This technique allowed for independent head movements in the virtual environment. The auditory soundscape included a binaural sound of city background noise. This sound was chosen to not include any jarring sounds, such as sirens, speech, or distinguishable car sounds. Additionally, three landmark sounds that corresponded to three visual landmarks in the scene were placed in the 3D soundscape around the user (see Figure 1 (b)). Depending on the condition, as for the visual environment, these three landmark sounds rotated around the user based on the chair rotation or were locked to the yaw axis, resulting in them being perceived in the same position around the user for the entire condition. Each condition was presented for 15 minutes in a separate session, except for *C1-NR* which was always presented first in the first session combined with one of the other conditions. This was done to avoid any cumulative effects of motion sickness.

Participants were seated on a rotating chair *(RotoVR*) which performed *Yaw* rotations while they wore a Vive Focus 3 VR headset [3]. The rotations performed by the chair were based on a script including *easy*, *medium* and *hard* rotations. Rotations were classified into these 3 groups based on the rotational speed. The chair's rotation speed can be set between 20 to 100. Rotations were defined as *easy* if the speed was between 20 and 40 (average of ≈25 deg/second), as *medium* if the speed was between 50 and 70 (≈35 deg/second) and as *hard* for speeds between 80 and 100 (≈45 deg/second). The rotations were presented in random order with rotations of the same type never being presented one after another. This motion profile was chosen based on pilot testing ensuring that the rotations would induce mild to moderate motion sickness. A prior study using the same rotational chair based the motion profile on an urban city drive, with fewer and less extreme rotations. This motion profile, however, resulted in an overall weak experiences of motion sickness making it less ideal as a testing tool [87].

The productivity task chosen for this study was based on the verbal reasoning section of the University Clinical Aptitude Test (UCAT) [1], which is used by UK universities to select applicants for their degree programmes. It is a reading comprehension task that measures the ability to read information and answer related questions. Text passages are between 200-300 words with two types of questions: "True, False, Can't Tell" questions or "free text" questions where four answer options are presented and the reader has to select the one that best applies. In its original form, the reasoning task has a time limit, however, due to the nature of our experiment we did not limit the time participants had to read the examples and answer the multiple choice questions. The reading examples were presented on a display in front of the participant in the VR HMD with 20-25 words being presented on each page (see Figure 2), covering roughly the central 10° of the visual field of the participant. Participants controlled their reading speed by pressing a button on the VR controller to move forward to the next page. After the text passage, the questions were presented with one per page (see Figure 2 right).

In the bottom right corner of the display, an attention task was presented as a secondary task for participants. This consisted of a dot that changed colour from green to red and *vice versa*. The time between colour changes ranged between 6 and 10 seconds. Participants had to press a button on the controller whenever a change in colour occurred. The task was based on work by Kooijman and colleagues [56] and was administered to ensure that participants visual attention was consistently focused on the display.

## 3.2 Measures

The following measures were used before, during and after each study condition to record the corresponding **dependant variables**:

**Motion Sickness** Participants filled out the Simulator Sickness Questionnaire (SSQ) [47] before and after each session, which determined their overall experience of motion sickness in each condition. While immersed in the virtual environment and exposed to the physical rotations, participants continuously rated their motion sickness on the Misery Scale (MISC) [11]. A visual representation of this scale was placed in front of them underneath the reading task displaying their current level of motion sickness allowing them to adapt this continuously if needed (see Figure 1). A condition terminated prematurely if participants reached a score of 7, which represents *fairly Nauseated* on the scale, to prevent participants from becoming too unwell. Participants were informed about the levels of the MISC scale prior to taking part and the threshold for terminating the experiment. The rapid administration of the scale allowed for the quantification of the time course of motion sickness.

**Mental Demand** The NASA-TLX [38] was administered at the end of each condition to assess perceived workload;

**Distraction of Environment** The level of distraction of the environment was rated on a 20-point Likert scale in the same style as the NASA-TLX items;

**Performance** Task performance was determined by the proportion of reading comprehension questions answered correctly as well as their overall reading speed;

**Presence** Participants filled in the Igroup Presence Questionnaire (IPQ) [102] after each condition to measure their sense of presence in the virtual environment. The IPQ uses 3 sub scales (Spatial Presence, Involvement and Realism) as well as an overall Presence score.

## 3.3 Participants

Twenty-three participants took part in this study, recruited through an internal recruitment system and each participant was compensated £40 when completing the study. Four participants terminated the experiment early as they were unable to tolerate the cybersickness symptoms (see results for more details). This resulted in a final sample size of 19 participants, who ranged in age from 19 to 41 years (M = 28.68, SD = 7.08). Ten participants identified as male, eight as female, and one as agender. Six participants had never used VR before, while the remaining 13 had various degrees of previous VR experience. Six of them had used VR less than 10 times prior to participating, while seven had extensive VR experience. All experimental procedures were approved by the University of Glasgow's Ethics committee.

## 3.4 Hypotheses

Based on the research questions and study design we formulated the following hypotheses:

***H1*** Conditions in which the visual background motion (vection cue) is congruent with physical chair rotations (*C3-V* and *C4-AV*) cause less motion sickness, higher presence and better task performance compared to conditions in which no visual background motion is presented (*C5-NC* and *C2-A*). Relating to RQ1 and confirming previous work [15, 46, 58, 70].

***H2*** Conditions in which auditory vection cues are in line with physical chair rotations (*C2-A* and *C4-AV*) cause less motion sickness, higher presence and better task performance compared to conditions in which sensory cues do not match chair rotation (*C5-NC*) (relating to RQ2).

***H3*** The combination of auditory and visual vection cues (*C4-AV*) should further reduce motion sickness and increase presence and task performance compared to just visual motion cues (*C3-V*) (relating to RQ3).

***H4*** Conditions with visual vection cues are perceived as more mentally demanding as more visual information (reading task, attention task and visual vections stimulus) are being processed (relating to RQ4).

***H5*** Higher experiences of motion sickness should result in lower levels of presence and a decrease in task performance (relating to RQ5).

## 3.5 Procedure

The experiment consisted of 4 sessions conducted on separate days. The first lasted around 45 minutes with the following three lasting around 30 minutes per participant. In the first session, participants received a brief introduction to the study and provided informed consent, they were shown the MISC and could familiarise themselves with the rating scale. Participants performed a training condition in VR while seated on the rotating chair to get used to the controls. During this training condition the chair was stationary to not induce any motion sickness. The training condition consisted of one reading example text passage followed by the four corresponding reading comprehension questions. This allowed participants to familiarise themselves with the controls for the reading task, attention task and motion sickness measure. After the training, participants filled in the pre-condition SSQ which was followed by condition *C1-NR*. After completing the 15 minute condition in VR, participants filled in the post-condition SSQ, the IPQ as well as the NASA-TLX workload rating. The four following conditions (*C2-A*–*C5-NC* were presented in counterbalanced order based on a latin square design. The first was presented within the first session, again proceeded by a pre-condition SSQ and followed by the post-condition SSQ, IPQ and NASA-TLX. The other three were presented in the following three sessions over the following days (one condition per session). Each session started with the pre-condition SSQ followed by the 15 min condition and concluded with the post-condition SSQ, IPQ and NASA-TLX. In the final session participants were debriefed and compensated for their participation.

# 4 RESULTS

## 4.1 Motion Sickness

Four participants did not complete all five conditions, dropping out either after *C2-A* or *C5-NC*. Nine of the 19 participants that completed the experiment dropped out of at least one of the five condition before the 15 minute session was completed due to reaching a MISC score of 7. Eight did not complete *C5-NC* (M=592.63s), similarly eight did not complete *C2-A* (M=608.97s) and one participant dropped out before completing *C3-V* (855.58s). Data from participants performing all conditions (N=19) was included in the analyses. Data from participants that dropped out of a condition prematurely was not excluded rather their last recorded motion sickness score, which was the highest possible (7) was recorded for the reminder of the condition [30].

Due to data not being normally distributed, we used a Friedman's ANOVA with pairwise Wilcoxon signed rank tests with Bonferroni correction for *post hoc* comparisons between conditions.

#### 4.1.1 *Motion Sickness Susceptibility and prior VR experience.*

An Individual's motion sickness susceptibility and their prior experience with VR has been argued to affect their experience of cybersickness as well as motion sickness [112]. To ensure that these individual differences had no effect on findings the relationship between participants motion sickness susceptibility and their experienced motion sickness in this study was investigated. No relationship was found between motion sickness susceptibility scores measured using the MSSQ [35] and the MISC ratings (using a repeated measure correlation [4] ; r=-.03, p>.798) or the SSQ scale (r=.06, p>.604). Similarly, individuals with prior VR experience did not differ in their experience of motion sickness here compared to individuals with no VR experience (using a Wilcoxon signed rank test; Average MISC: W=21, p=.127; Max MISC: W=22.5, p=.159; SSQ: W=59, p=.089). Individuals with VR experience could be more resilient to solely visually induced motion sickness but not to motion sickness induced by physical motion in combination with VR.

#### 4.1.2 *Average Misery Scale Scores.*

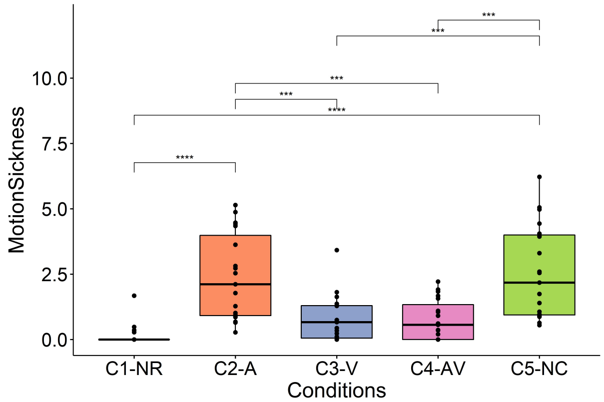
Motion Sickness ratings differed significantly between the conditions, $\chi^2(4)$=51, p<.001, W=.672. *Post hoc* tests revealed significant differences in Motion Sickness scores between *C2-A* (M=2.29, SD=1.64) and *C1-NR* (M=0.15, SD=0.40, p<.001), *C3-V* (M=0.78, SD=0.87, p<.001) as well as *C4-AV* (M=0.76, SD=0.18, p<.001) and between *C5-NC* (M=2.55, SD=1.78) and *C1-NR* (p<.001), *C3-V*(p<.001) and *C4-AV* (p<.001) (see Figure 3 (a)).

#### 4.1.3 *Maximum Misery Scale Scores.*

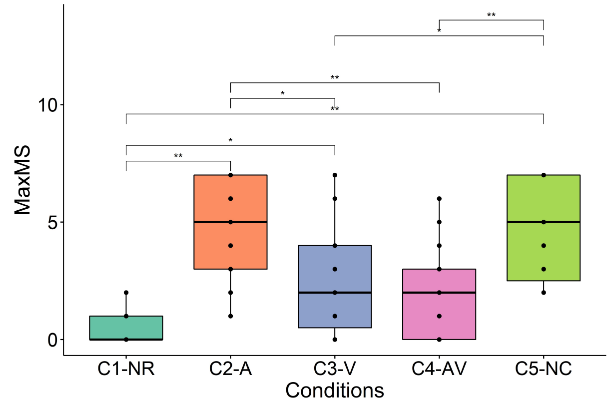
Maximum Motion Sickness ratings differed significantly between the conditions, $\chi^2(4)$=52.7, p<.001, W=.693. Pairwise Wilcoxon signed rank tests between conditions revealed that *C2-A* (M=4.89, SD=2.18) resulted in significantly higher maximum motion sickness ratings compared to *C1-NR* (M=0.53, SD=0.77, p=.001), *C3-V* (M=2.32, SD=2.08, p=.011) and *C4-AV* (M=1.80, SD=0.41, p=.004). Similarly, *C5-NC* (M=4.84, SD=2.14) resulted in higher maximum motion sickness ratings compared to *C1-NR* (p=.001), *C3-V* (p=.01) and *C4-AV* (p=.003). *C1-NR* had significantly lower maximum motion sickness score than *C3-V* (p=.036) (see Figure 3 (b)).

#### 4.1.4 *SSQ Scores.*

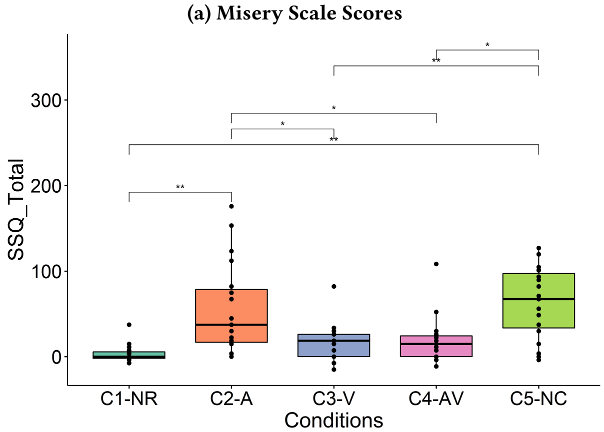
Analyses of the three sub-scales (Nausea, Oculomotor, Disorientation) showed similar results to the overall SSQ, so, for brevity, we only report results for total SSQ score. SSQ scores differed significantly between the conditions, $\chi^2(4)$=38.3, p<.001, W=.504. *Post hoc* analysis revealed significant differences between *C2-A* (M = 56.7, SD = 52.2) and *C1-NR* (M=3.15, SD=10.8, p=.002), *C3-V* (M=16.7, SD=21, p=.019) and *C4-AV* (M=18.1, SD=26.7, p=.026),



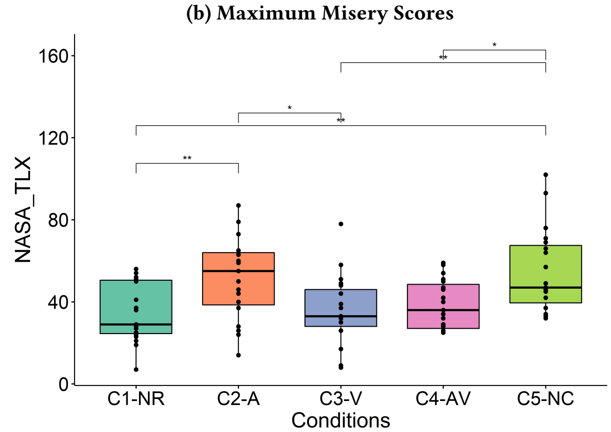

(a) Misery Scale Scores




(b) Maximum Misery Scores




(c) SSQ Scores




(d) NASA-TLX Scores

**Figure 3: (a) Mean MISC scores, (b) the maximum motion sickness experience on the MISC scale, (c) SSQ scores, (d) NASA TLX scores. Black lines representing the median and the colour of the boxes representing the five conditions: *C1-NR*: Dark green, *C2-A*: Orange, *C3-V*: purple, *C4-AV*: Pink, *C5-NC*: light green**

and then between *C5-NC* (M=62.8, SD=41.2) and *C1-NR* (p<.001), *C3-V* (p=.008) and *C4-AV* (p=.015) (see Figure 3 (c)).

*4.1.5 Development of Motion Sickness over Time for the five Conditions.* A linear mixed effect model was performed to investigate the effects of condition and time on motion sickness. A significant effect of Condition (F(4,2822)=2.59, p=.035, $f^2$=.58), time (F(1,2822)=1239.59, p<.001, $f^2$=.41) and their interaction (F(4,2822)=147.16, p<.001, $f^2$=.13) on motion sickness ratings was found. Motion Sickness increased with time particularly for *C2-A* and *C5-NC* as well as for *C2-A* and *C3-V*. *C1-NR* was not affected by time as there was no chair rotation in the baseline condition (see Figure 4).

## 4.2 Mental Demand and Distraction

*4.2.1 NASA TLX.* Overall NASA TLX scores differed significantly between the conditions, $\chi^2$(4)=34.36, p<.001, W=.452. *Post hoc* analysis revealed significant differences in perceived Work load between *C2-A* (M=52.4, SD=21.1), *C1-NR* (M=34.7, SD=14.3, p=.007) and *C3-V* (M=36.1, SD=16.7, p=.019), and between *C5-NC* (M=54.8, SD=20.5) and *C1-NR* (p=.004), *C3-V*(p=.005) and *C4-AV*(M=38.5, SD=12.15, p=.011).

*Physical Demand* scores differed significantly between the conditions, $\chi^2$(4) = 43.5, p<.001, W=.573. *Post hoc* analysis revealed that *C1-NR* (M=1.21, SD=1.65) was perceived as less physically demanding compared to all other conditions: *C2-A* (M = 7.21, SD = 5.66, p=.003); *C3-V* (M=3.95, SD=3.17, p=.003); *C4-AV* (M=3.26, SD=3.05, p=.004); *C5-NC* (M=7.26, SD=5.23, p=.002). *C3-V* (p=.019) and *C4-AV* (p =.019) were also rated as less physically demanding than *C5-NC*.

*Effort* scores differed significantly between the conditions, $\chi^2$(4)=19.9, p<.001, W=.261. *Post hoc* analysis revealed that *C4-AV* (M=7.00, SD=4.22) had less perceived effort than *C5-NC* (M=11.4, SD=4.55, p=.018).

*Frustration* scores differed significantly between the conditions, $\chi^2$(4)=20.3, p<.001, W=.268. *Post hoc* analysis revealed that *C3-V* (M=3.47, SD=3.73) and *C4-AV* (M = 3.42, SD = 3.13) were less frustrating than *C2-A* (M=8.00, SD=5.66, *C3-V*: p=0.18, *C4-AV*: p=0.29) and *C5-NC* (M=8.42, SD=5.87, *C3-V*: p=0.14, *C4-AV*: p=0.11).

*4.2.2 Distraction of Virtual Environment.* Distraction ratings did not differ significantly between the conditions, $\chi^2$(4)=2.78, p=.596,

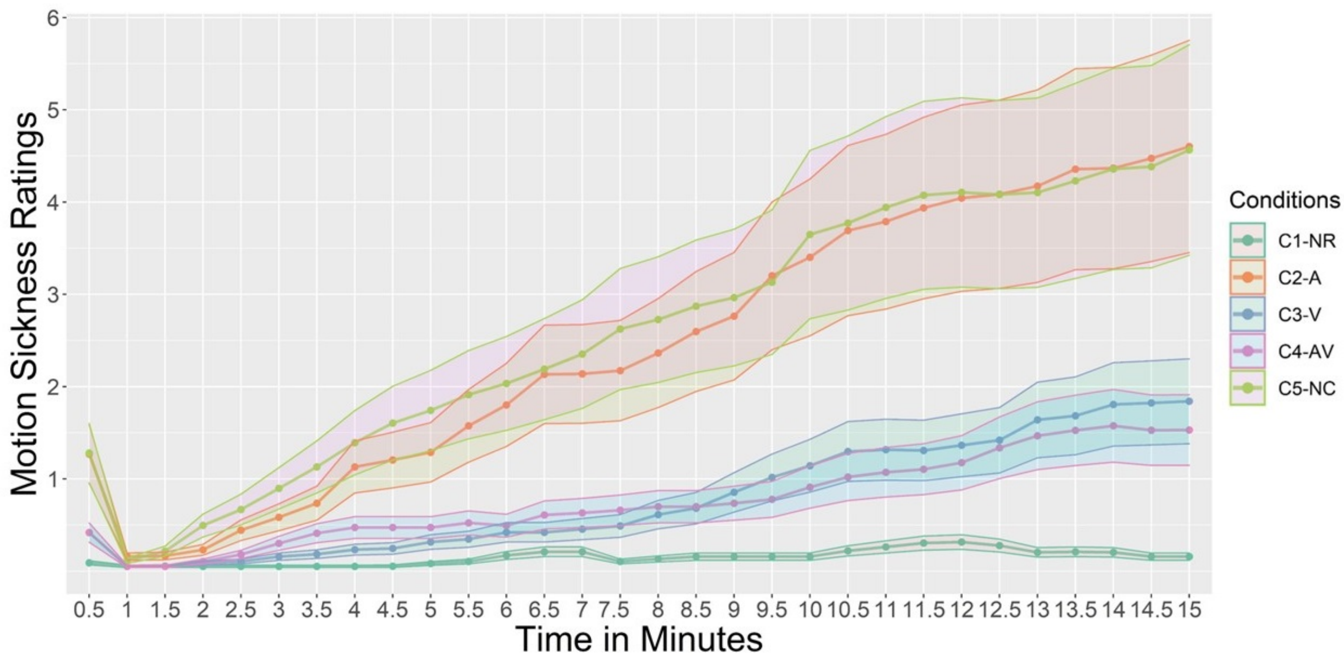



**Figure 4: Development of motion sickness over time for the 5 conditions. Shaded areas represent 90% confidence intervals. Y-axis represents MISC Scale values, participants were able to rate their level of motion sickness: 0: "no problems", 1: "some discomfort" 2-5: "vague to severe dizziness", 6: "little nauseated", 7: "rather nauseated".**

W=.037. Participants were similarly distracted from the environment in all condition (*C1-NR*: M=6.0, SD=5.58; *C2-A*: M=7.63, SD=5.27; *C3-V*: M=5.74, SD=4.95; *C4-AV*: M=5.16, SD=4.07; *C5-NC*: M=7.68, SD=5.86).

## 4.3 Performance on Task

*4.3.1 Responses.* To investigate participants performance in answering the reading comprehension questions a binary logistic regression model was performed. No significant difference in participants performance was found between the conditions, $\chi^2(4)$=4.61, p=.329. In all conditions, participants answered around half of the questions correctly (*C1-NR*: M=50.51% (±.025 SE); *C2-A*: M=45.50% (±.028 SE); *C3-V*: M=51.31% (±.026 SE); *C4-AV*: M=48.67% (±.025 SE); *C5-NC*: M=45.64% (±.027 SE))

*4.3.2 Reading Speed.* No significant difference in reading speed was found between the conditions, $\chi^2(4)$=7.89, p=.096, W=.104. Participants read approximately the same number of passages in each condition (*C1-NR*: M=5.18, SD=1.54 ; *C2-A*: M=4.24, SD=1.97; *C3-V*: M=5.03, SD=1.38; *C4-AV*: M=5.46, SD=1.90; *C5-NC*: M=4.38, SD=1.91).

*4.3.3 Relationship of Motion Sickness and Performance.* A repeated measures correlation [4] was performed to investigate the relationship between motion sickness and participants performance on the reading task. Performance on the reading comprehension task (r=-.23, p=.044) as well as reading speed (r=-.57, p<.001 ) correlated negatively with average motion sickness ratings. Reading speed also correlated negatively with maximum motion sickness ratings (r=-.46, p<.001). Neither performance nor reading speed correlated with SSQ scores (performance: r=-.07, p=.493; Speed: r=-.09, p=.429).

## 4.4 Presence

*4.4.1 Conditions.* Analyses of the three IPQ sub scales (Spatial Presence, Involvement and Realism) showed similar results; hence, for brevity, we only report results for the overall IPQ scores. Presence scores did not differ significantly between the conditions, $\chi^2(4)$=3.18, p=.529, W=.042. Participants experienced a similar sensation of presence in all condition (*C1-NR*: M=43.1, SD=9.14 ; *C2-A*: M=40.2, SD=9.46; *C3-V*: M=44.3, SD=11.3; *C4-AV*: M=43.5, SD=10.6; *C5-NC*: M=40, SD=12.5).

*4.4.2 Relationship of Motion Sickness and Presence.* A repeated measures correlation [4] was performed to investigate the relationship between participant experience of motion sickness and presence. Spatial presence negatively correlated with average Motion Sickness ratings (r=-.33, p=.004), Maximum Motion Sickness ratings (r=-.29, p=.010), total SSQ scores (r=-.27, p=.018), Oculomotor scores (r=-.31, p=.006) and Disorientation scores (r=-.29, p=.011). IPQ total scores negatively correlated with average Motion Sickness scores (r=-.33, p=.003) and Max Motion Sickness scores (r=-.23, p=.041). Involvement correlated negatively with average Motion Sickness scores (r=-.24, p=.038) and Realism showed no relationship with any of the motion sickness measures.

# 5 DISCUSSION

## 5.1 Summary of Findings

Our results demonstrate for the first time the potential of semantic uni- and multi-sensory vection cues in reducing motion sickness elicited by physical rotations, as measured both for the continuous MISC ratings reported throughout the 15 min sessions as well as SSQ scores collected after each session. Conditions with visual vection cues also resulted in lowest perceived mental demand. Adding auditory vection cues to visual vection cues showed some additional beneficial effects in terms of maximum motion sickness scores. The condition combining both visual and auditory motion cues also resulted in the lowest frustration scores and was rated as the least physically demanding out of all the conditions that included rotations of the chair. Experiencing stronger motion sickness also resulted in lower experienced presence and task performance. Contrary to predictions, neither performance nor presence were affected by the multi-sensory cue combinations.

*5.1.1 Visual Vection Cues Effectively Mitigate Motion Sickness.* The MISC and SSQ results showed support for Hypothesis **H1**; conditions in which the visual background moved congruently with physical rotations (*C3-V*, *C4-AV*) reduced the motion sickness symptoms experienced while performing the reading task and after exposure to physical rotations and virtual environment.

*5.1.2 Auditory Vection Cues Did Not Effectively Mitigate Motion Sickness.* Our data were not able to support Hypothesis **H2**, which predicted that conditions with auditory vection cues providing the same information about self-motion as physically perceived motion should reduce motion sickness symptoms. Auditory motion cues on their own showed no beneficial effects with condition *C2-A* resulting in similar MISC and SSQ scores as condition *C5-NC*. These results could be explained by the weaker nature of auditory vection cues compared to visual ones (e.g.[96]). Auditory vection cues elicit a weaker sensation of vection which could have been insufficient to elicit enough self-motion in the participants to counter the strong physical motions perceived from the chair rotations. We suspect that auditory vection cues on their own might be more effective in mitigating motion sickness elicited by slower and gentler physical movements.

These results might also be explained by the conflict between the visual and vestibular cues overshadowing the beneficial effects of the congruent auditory vection cues (*C2-A*). In the current study the visual vection cues in the background were stationary creating a conflict between the visual and vestibular system. The auditory cues might be more beneficial if no mismatching visual cues were presented in the background, due to visual vection being perceived as the stronger vection cue and thereby overshadowing the auditory vection cue. We chose to integrate stationary visual and auditory cues to keep the sensory information perceived by the participant as constant as possible between conditions.

Auditory motion cues, independent of their direction, may be interpreted to be in line with the visual vection cues [104]. If a visual vection cue, for example, indicates upward self-motion, an auditory vection cue is likely to be interpreted as giving information about self-motion in the same direction independent of its actual direction. This could explain the findings in this study given that the condition in which visual and auditory motion cues were incongruent with vestibular motion cues (*C5-NC*) caused similar levels of motion sickness as the condition in which the auditory vection cues were congruent with the vestibular motion cues but with visual cues being incongruent (*C2-A*). The auditory motion cues were interpreted as being in line with the visual ones, resulting in both of these conditions being perceived as being identical, and therefore, causing the same degree of discrepancy between the sensory systems and hence motion sickness.

The type of auditory cues used could potentially have introduced discomfort in the participants unrelated to their sensation of vection. For example the volume of the sounds could have been somewhat uncomfortable (too loud) and could thereby have contributed to higher motion sickness ratings [84]. Participants were however, ask before every session whether the audio was at a pleasant volume and they could change the volume when needed. The type of sounds chosen could have also been perceived as uncomfortable. Based on vection literature on the effectiveness of stimulus attributes in vection cues, we decided on semantic auditory cues that matched objects in the virtual scene (church bell - church, bird noise - park, construction noise - construction site). These sounds could have been perceived as unpleasant by participants which could have also negatively affected their motion sickness ratings [49, 53]. Sounds were, presented in all conditions, just their spatial directionality varied, if the simple addition of a soundscape or the type and volume of the sound had an effect on participants' motion sickness level this should have been the same for all conditions. Spatial auditory vection cues that were congruent with visual and vestibular cues (*C4-AV*) had beneficial effects on motion sickness and overall comfort of participants highlighting the positive effects of multi-sensory cue integration.

*5.1.3 Multi-Sensory Vection Cues Beneficial Across Measures.* Auditory vection cues showed beneficial effects when combined with visual vection cues (*C4-AV*). Maximum experienced motion sickness throughout the sessions was the lowest of all conditions in which the chair was rotating, suggesting that auditory motion cues enhance the motion sickness mitigation capabilities of visual vection cues. The combined condition was also perceived as the least frustrating and least physically demanding of all conditions. Even though auditory vection cues on their own did not seem to have beneficial effects on motion sickness in this study, when combined with visual vection cues they seem to enhance the users experience of the virtual environment and reduce the intensity of motion sickness symptoms perceived.

*5.1.4 Presence and Task Performance.* Hypotheses **H1, H2 and H3** proposed that the addition of sensory cues should have beneficial effects on experienced presence and task performance. The addition of visual or multi-sensory vection cues in line with physical motion cues was expected to result in higher presence scores and increases in task performance, with the combined cue condition (*C4-AV*) in which all three sensory motion cues (visual, auditory and physical) were in line was expected to result in the highest presence scores and best task performance. The results of this study cannot confirm this notion; multi-sensory cue integration seemed to have no effect on participants task performance or experienced presence.

The sensory self-motion cues were unrelated to the primary reading task performed while immersed in the virtual environment therefore they might have been perceived as separate from the task which could explain why their addition did not benefit task performance. Similarly, participants' sense of presence measured by the IPQ could have related mainly to their attentional focus on the reading task rather than the virtual environment made up of the visual and auditory landscapes, which would explain why a variation in the motion information provided by these sensory cues had no effect on perceived presence in the task.

Adding visual motion stimuli covering a large amount of the available visual field did not negatively affect perceived mental demand, suggesting that the addition of these stimuli does not distract or negatively affect performance on a primary cognitive task (e.g., reading), contradicting Hypothesis **H4** and contradicting previous work [88]. The effects of our multi-sensory cues on perceived mental demand reflected our findings for motion sickness, suggesting that rather than visual or sensory demand in general, motion sickness was the driving factor behind the perceived mental demand in the task.

Based on our findings, we hypothesise that the vection cues presented in this study were perceived as a separate part of the virtual environment to the reading task. Their addition had no effect on perceived presence in the virtual environment or on task performance. These findings suggest that VR developers can design virtual environments that include visual and auditory vection cues without having to adapt them to specific cognitive tasks meaning that they could then use the same effective visual motion sickness mitigation cue for a variety of productivity tasks, such as reading or writing.

Rather than differences between the five conditions (differences in the presented visually and auditory vection cues) ones experience of motion sickness related to participants experience of presence and task performance. Results were in support of Hypothesis **H5**: increases in motion sickness symptoms resulted in reduced task performance and a reduced sense of presence. These results highlight the need for VR designers and developers of automated vehicles to find a way to create a travel journey for passengers that is motion sickness free and can be used productively. Eliminating motion sickness from car journeys of the future is essential to enable productive work and enjoyable game play for travellers.

## 5.2 Limitations

Our work has some limitations. Firstly, the physical motion presented in our experiment was not fully representative of vestibular motion perceived as a passenger in a moving vehicle. Motion sickness in this study was elicited by yaw rotations only. To be representative of true vehicle motion, linear motion, pitch and roll need to be included. In the visual scene the participants are placed in a fixed location rotating around the same axis rather traveling through a city scene going around corners which could be perceived as some what unnatural. However, this visual stimulus was chosen deliberately to avoid adding visual self-forward vection cues the addition of such visual linear motion could be a confounding variable adding additionally visually-induced motion sickness.

The yaw rotation profile was chosen for this study to induce moderate motion sickness, allowing us to investigate the beneficial effects of visual and auditory vection cues in the lab in a highly controlled study. This also allowed us to investigate the beneficial effects of visual and auditory vection cues on motion sickness for rotational motion separately from linear motion. Vection cues of different sensory modalities could be more or less effective for different motion profiles (rotation vs. linear).In future work mitigating motion sickness for real life car journeys the vection cues could then be integrated when most efficient, different cues could be introduced for turns of the car than for periods of acceleration or deceleration. It is therefore, important to test the effectiveness of such mitigation cues separately for rotational and lateral motion profiles. We suggest that another controlled study investigating the effectiveness of these sensory vection cues on a lateral motion track is needed. This will then inform future research investigating the effectiveness of such cues on more complex vehicle motions. If for example, auditory cues are more effective for rotational motion they can be directly applied to turns of the vehicle while only visual cues are displayed to mitigate motion sickness occurring from acceleration and deceleration of the vehicle. In conclusion the effectiveness of visual and auditory vection cues in reducing motion sickness needs to be tested in another controlled study for lateral motion as well as outside the lab to identify what sensory cues are most suitable for what motion profiles and in combination with what cognitive task.

The motion profile experienced by participants was chosen to elicit motion sickness in a short period of time, it is therefore more provocative than a standard city drive in terms of the experienced rotations. Future research should address the applicability of our findings to other motion profiles, but we reaffirm our findings form a foundation for further research into the effectiveness of multi-sensory vection cues in reducing motion sickness.

We chose 15 min for the duration for our condition. This time was chosen to minimise severe motion sickness symptoms being experienced by participants and to ensure that the study duration for each participant was kept at a reasonable time (4 sessions 2h:15min). Such a short duration is, however, not fully representative of a productivity task. Motion sickness symptoms increase over time (see Figure, 4) [48] it is therefore important to test the effectiveness of vection cues for mitigation for longer duration to test whether such cues can help reduce maximum motion sickness levels reached during longer journeys or postpone the onset of motion sickness symptoms in general or the onset of severe symptoms.

Participants' motion sickness development over time revealed an unexpected pattern with ratings starting out higher and returning back to base level within the first minute of exposure (see Figure, 4). This finding could be due to an initial rise in motion sickness when first exposed to the physical rotations and virtual environment or could be due to participants trying out the joystick to indicate their ratings, they were asked to only do this in the training, however, we can not conclude with certainty whether this finding reflects an actual experience of motion sickness or is solely due to study design.

Finally our reading task was presented on a small virtual display in the centre of participants visual field. The size of display was chosen to ensure a large enough part of the visual field would be covered by the visual vection stimulus. The size restrictions of the display could potentially have limited reading performance. In follow up work a baseline for reading performance outside VR should be recorded to find out whether our set up has negative effects on passengers reading performance. Should this be the case sensory vection cues other than visual ones could be used in that case to mitigate motion sickness without taking over large parts of the display. The design of how the reading task was displayed could have also affected participants' experience of motion sickness. The display follows the participant while rotating being presented in front of them at all times, potentially being perceived as a rest frame object. The addition of rest frames has been shown to reduce visually induced motion sickness in VR [124], such an effect of the rest frame would, however, be the same in all conditions. The design of the reading task was chosen for ecological validity of the task. Display set ups using one or multiple displays similar to the one presenting our reading task are being used in VR [68, 75]. The aim of this study was to identify vection cues that are effective in reducing motion sickness while a productivity task is performed, without hindering performance on such a task. The reading comprehension task is representative of productivity task generally performed when working in VR, such as reading emails, articles or word documents. Using another cognitive task could have undermined the validity of the use case.

## 5.3 Implications and Challenges for Passenger VR Design

*5.3.1 Semantic Vection Cues are an Effective Motion Sickness Mitigation Technique.* Based on our findings we recommend that when creating VR applications to be used during travel, VR developers need to pay particular attention to the sensory motion cues presented in the virtual environment. Presenting incongruent visual vection cues to an individual experiencing physical motion can lead to enhanced motion sickness which means they cannot work productively or enjoy their journey. Our results show that semantic visual background motion is successful in mitigating motion sickness without distracting from cognitive tasks performed at the same time. We would therefore recommend that VR developers choose strong vection stimuli, such as semantic stimuli, to visually integrate the motion of the vehicle into the virtual environment. This will allow them to keep motion sickness levels as low as possible and productivity up.

*5.3.2 Multi-Sensory Cue Combinations Recommended.* When it comes to sensory cue combination we would also recommend that auditory vection cues should not be presented in combination with incongruent visual vection cues. When visual vection cues are presented that are not congruent with physical motion, the addition of auditory vection cues enhances the conflict between the visual and vestibular system, rather than decreasing it. Auditory vection cues are, however, useful additions alongside visual vection cues congruent with physical motion. In this scenario, they can further mitigate motion sickness and improve overall comfort in the environment by reducing physical demand and frustration.

*5.3.3 Challenges in Facilitating VR Motion Sickness Mitigation in Practice.* For the mitigation strategies to work in real moving vehicles, VR developers will need low-latency access to velocity (acceleration, deceleration), orientation and possibly location data of the vehicle. There are some tentative systems allowing for the integration of such data into the virtual user experience [2, 14, 15, 72]. Some of which are commercially available only [2] and others which are promising open access [72] making VR development for travel applications possible and easy to implement for VR developers in the near future.

*5.3.4 Facilitating Productivity Tasks during Travel.* The addition of our vection cues has enabled participants to perform a productivity task (reading) during motion without it being overly motion sickness provoking. This is bringing us a step closer to giving VR designers an effective strategy that will support in-car VR productivity. It is important to not only test the effectiveness of motion sickness mitigation strategies on their own but also in combination with productivity tasks, as the nature of the task might influence the effectiveness of the mitigation strategy [10, 80, 129].

*5.3.5 Other VR and XR use cases.* Even though this paper focused primarily on VR and the effectiveness of the introduced mitigation strategies for a VR headset, we suggest that recommendations made here for VR developers can also be applied to other XR use cases, such as for AR. Auditory feedback could for example be used as a mitigation strategy when using AR headsets, bolstering the available visual perception of motion through car windows. Similarly optic flow patterns could be overlayed over the interior of the vehicle (which occludes visibility of the outside world) using an AR headsets helping to potentially mitigate the motion sickness of the user; in-time, such cues could even be integrated into other tasks, such as game play [118]. These findings could also transfer to other VR and XR use cases - the introduced mitigation strategies could be integrated in various types of transportation, such as on busses, planes or trains and they could transfer to other types of motion simulators as well, such as driving or flight simulators. They could also be integrated into VR theme park rides, that make use of motion platforms to ensure that passengers experience a realistic ride without feeling motion sick. The auditory vection cues can also be integrated into the car environment independent of a XR headset, for example the auditory environment of the vehicle could be augmented using existing speakers to more strongly convey auditory vection helping to mitigate motion sickness. Auditory vection-type cues could also be further interleaved into motion simulators improving the training experience; and they could be included in other motion environments such as roller coasters, where VR is already being used to enhance the ride experience [5, 13]. Further work would be needed to validate the transfer of our findings, and identify yet more effective auditory cues. In conclusion, our research underlines that more consideration should be given to multimodal (rather than just visual) cue design when resolving sensory mis-match.

## 5.4 Implications and Challenges for Understanding, and Mitigating, Sickness

*5.4.1 Best Practice in Motion Sickness Studies.* With this study we also aim to highlight the need to ensure best practice in motion sickness research. We recommend that to minimise the cumulative effects of motion sickness to affect study design and findings, study sessions should be held on separate days, with at-most one 'in-motion' condition per session per day. Whilst a common standard in traditional motion sickness research, as research into this phenomenon has increased, particularly within the HCI domain driven by new mitigation technologies and in-transit use cases [40, 65, 69, 71, 118], such standards have been less rigorously followed, due to their high logistical and time cost and the consequent impact on participant recruitment and retention. Instead, multi-disciplinary work often relies on giving participants breaks between conditions, to allow motion sickness ratings to return to a baseline level before starting the next condition. However, despite such recovery breaks, the prior experience of motion sickness can still affect how fast, and to what extent, motion sickness is experienced in the following condition.

Secondly, the motion profiles participants are exposed to should be controlled enough so they can be held constant between conditions. This can be hard to do in on-road research, with the researcher often not able to control the traffic or the road conditions. Or it can be rather expensive having to book a motion platform or track for multi-session studies. Despite this cost, controlled motion sickness studies are crucial if we are to appropriately validate motion cues and other mitigation strategies.

*5.4.2 Towards Common, Validated Measures and Reporting.* In this study we collected a continuous measure of motion sickness using the MISC as well as an overall measure of motion sickness using the SSQ as these are two often used measures of motion sickness. To allow for comparisons of findings between studies and to allow for easy replication, the motion sickness research community should establish guidelines on which motion sickness measures to use for which scenarios and how they should be applied.

*5.4.3 The Need to Further Consider Auditory Motion Cues.* Our findings hint at the potential of auditory vection cues, particularly in conjunction with visual cues, as well as the need to further investigate their effectiveness in mitigating motion sickness and enhancing comfort during travel. We found no beneficial effects of congruent auditory vection cues in relation to physically perceived self-motion when presented in combination with incongruent visual vection cues. This could partly be due to the design of our experiment. To keep conditions as similar as possible, we included visual backgrounds that were stationary in the conditions without visual vection cues (*C2-A*, *C5-NC*) and similarly we included stationary auditory cues in the conditions without auditory vection cues (*C3-V*, *C4-AV*). The addition of incongruent visual cues in condition *C2-A* could have masked the beneficial effects of the auditory vection cues. Future work should not only investigate the beneficial effects of auditory cues for different motion direction but also separate them from any incongruent visual vection cues.

We suggest auditory vection cues could show potential in mitigating motion sickness for less sickness inducing environments or for other motion profiles such as linear acceleration and deceleration when no incongruent visual motion is present. Moreover, our study investigated the effectiveness of one type of auditory cue, however more detailed or varied auditory soundscapes (e.g. inspired by auditory mixed reality research [67] or based on route affordances [45]) could show differing beneficial effects. Moreover, using music based auditory cues that are perceived as more pleasant could also show beneficial effects based on their positive emotional properties [49, 53].

*5.4.4 Exploring Additional Modalities for Multi-Sensory Motion Cues.* In demonstrating the efficacy of multi-sensory motion cues leveraging vection research, we open the door to the design of novel motion cues that better integrate into the passenger experience and enhance visual cue efficacy. For example, haptic stimuli could be introduced to enhance comfort and mitigate motion sickness during journeys [125, 128]. Haptic stimuli have the advantage over both visual and auditory ones in that they rely on a sensory system that is more than likely not needed to perform most productivity or entertainment based activities that a passenger would perform during car journeys. Passengers might be on a video call while commuting to their workplace using both visual and auditory senses, and in such a scenario using auditory or visual vection cues could distract from the task at hand or take up perceptual space that could be better used to support the task at hand. Hence haptic vection cues could be the ideal alternative mitigation technique to ensure a pleasant journey for passengers. Future work investigating the effects of different sensory vection cues as well as their effects when combined is needed. An additional focus should be put on identifying the ideal combination of cues for different scenarios. What cues are most suitable when watching a movie, which ones are best when reading and what ones are best in mitigating motion sickness when on a call?

*5.4.5 Real-time Versus Anticipatory Motion Cues.* Finally, we presented vection cues that were congruent and presented simultaneously with physical motion. A major contributor to motion sickness in a moving vehicle is not knowing what motion is coming next [24, 59]. Knowing where the vehicle is turning next and/or being able to see the trajectory that the vehicle will follow can reduce symptoms of motion sickness [8, 24, 37, 59, 74]. Providing passengers with additional anticipatory cues in combination with our cues could result in an even greater reduction of motion sickness symptoms. These anticipatory cues could also be perceived as less distracting as they only have to be presented when orientation or velocity of the vehicle changes and not constantly. This study demonstrates a viable platform for a controlled examination of anticipatory motion cue effects on rotational motion as well as highlighting possibilities of using multi-sensory cues driven by VR or other XR devices to better amplify capabilities of anticipatory motion cues.

# 6 CONCLUSIONS

In this paper, we investigated the effects of adding visual and auditory self-motion cues to a reading task presented in VR for mitigating motion sickness. We also explored how these stimuli on their own and combined affect participants motion sickness, sense of presence and perceived workload and performance. We used an experimental set up in which participants were seated on an actuated rotating chair experiencing yaw rotations. Our results indicated that visual vection cues can mitigate symptoms of motion sickness and that the addition of auditory vection cues further reduced motion sickness and increased perceived comfort. This is important as it highlights the potential of using multiple sensory vection cues in combination to reduce motion sickness and improve the overall experience of passengers. The integration of such vection cues helps unlock the potential for productivity in transit using XR, demonstrating that a productivity task can be intermixed with motion cues with no degradation of workload or performance, while minimising motion sickness. We highlighted the need for developers of XR applications to be used by travellers to include motion sickness mitigation strategies as without them performance on cognitive tasks such as reading was significantly reduced. We discuss how the findings of this study can guide such development and reflect on best practice and open challenges for both XR designers and motion sickness research. If we can solve the problems of motion sickness. XR headsets are poised to become an integral part of the travel experience in the future, with the potential to turn constrained physical spaces into limitless virtual worlds, and to do so whilst serving as a motion sickness mitigation tool. Our research takes us one step closer to this reality, further evidencing the utility of XR-driven multi-sensory motion cues and provoking new directions in motion cue design.

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