I Am The Passenger: How Visual Motion Cues Can Influence Sickness For In-Car VR

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ABSTRACT
This paper explores the use of VR Head Mounted Displays (HMDs) in-car and in-motion for the first time. Immersive HMDs are becoming everyday consumer items and, as they offer new possibilities for entertainment and productivity, people will want to use them during travel in, for example, autonomous cars. However, their use is confounded by motion sickness caused in-part by the restricted visual perception of motion conflicting with physically perceived vehicle motion (accelerations/rotations detected by the vestibular system). Whilst VR HMDs restrict visual perception of motion, they could also render it virtually, potentially alleviating sensory conflict. To study this problem, we conducted the first on-road and in motion study to systematically investigate the effects of various visual presentations of the real-world motion of a car on the sickness and immersion of VR HMD wearing passengers. We established new baselines for VR in-car motion sickness, and found that there is no one best presentation with respect to balancing sickness and immersion. Instead, user preferences suggest different solutions are required for differently susceptible users to provide usable VR in-car. This work provides formative insights for VR designers and an entry point for further research into enabling use of VR HMDs, and the rich experiences they offer, when travelling.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords
In-motion; In-car; Automobile; Autonomous Car; Passenger; Virtual Reality; Mixed Reality; Motion Sickness; HMD;

INTRODUCTION
For many travellers, a long journey is not to be relished. Journeys can last for significant durations, for example car journeys in UK last on average 22 minutes [17], with commutes lasting 55 minutes [58]; in the USA, drivers spend 56 minutes a day on average in-transit [76]. These journeys can be repetitive (e.g. the commute to work), with travellers frequently noting that such trips are wasted time [24, 80]. Whilst collocated social interaction can offer some respite [33], journeys are often conducted without the physical presence of friends or family, with the car providing solitary personal space [24]. Entertainment and productivity options are limited to displays significantly smaller than those in the home or office (e.g. phones, tablets, laptops, dashboards and rear-seat systems [81]). In the specific case of car journeys, these issues will gain increasing prevalence given the arrival of fully autonomous cars, which would free drivers from the driving task, and consequently increase the occurrence of passenger experiences.

While autonomous cars will allow for radical redesign of the car interior (e.g. seating locations and internal display configurations [20]), passengers will still perceive themselves as being in a constrained space, with the physical limitations of the interior dictating what is possible to be rendered and displayed. Moreover, the passenger's visual perception of motion may be compromised by use of these displays, through changes in gaze angle (e.g. looking down/away from windows) and occlusion (presenting content over windows, or occluding windows to enhance immersion [43]). This has implications for motion sickness, which in-part arises from the sensory mismatch of visually and physically perceived motion [59, 85].

Many people become travel sick when watching TV, reading or working in vehicles, meaning that they cannot use the time productively. These problems will grow in number with the arrival of autonomous cars [20, 19, 71]; the act of driving stops many people from feeling sick due to the anticipatory cues of being the driver [75] and without these cues people who did not get sick will now do so. Consideration needs to be given to how entertainment and productivity can be supported whilst minimizing motion sickness. Virtual Reality (VR) and Augmented Reality (AR) Head Mounted Displays (HMDs) have the potential to significantly expand the display space, enabling immersive entertainment and workspaces that go beyond the physical limitations of the car interior. Problematically, VR HMDs also occlude visual perception of reality [44, 6] and thus the car's motion, and are likely to lead to sensory mismatch and, consequently, motion sickness. However, assuming the orientation and velocity of the vehicle can be tracked at low latency, HMDs have the potential to portray the vehicle motion virtually. Accordingly, for both VR HMDs, and passengers more generally, the problem of occluding the visual perception of motion, and the resultant sensory mismatch this causes, can be solved (as demonstrated in consumer VR rollercoasters which run over a known and precisely controlled route [77]). VR and AR HMDs are capable of conveying the motion of the vehicle at all times, from all viewing angles. Consequently, the problem is then: how should these

CHI 2017, May 06 - 11, 2017, Denver, CO, USA

ISBN 978-1-4503-4655-9/17/05. . . $15.00
DOI: http://dx.doi.org/10.1145/3025453.3026046

dynamic and unpredictable physical motions be visually presented, and how can they be integrated into any virtual scene without reducing the immersion of the VR content.

This paper examines VR HMD use in-car, in-motion for the first time. Through a user study, we investigate whether consuming stationary 360° VR content in-car and in-motion induces motion sickness. We examine this both for existing consumer VR HMDs that interpret rotations of the car as rotations of the HMD, and future positionally-tracked HMDs that do not. We also examine to what extent motion sickness can be rectified by conveying motion peripherally, allowing for physical motion cues to be combined with any VR content. New baselines for VR motion sickness in-car are established and guidelines for future experimentation are provided, before we finally explore the further research required to enable comfortable VR HMD use in-motion.

RELATED RESEARCH

Motion Sickness

Motion sickness refers to illness arising from a person being within a motion environment, such as a moving vehicle [59]. Symptoms of motion sickness typically include cold sweat, dizziness and nausea/vomiting [52]. The predominant theory is that it arises due to sensory conflicts (also sensory re-arrangements or sensory mismatch), as first discussed by Reason and Brand [59]) between what Bertolini *et al.* describes as motion-sensitive input signals [3]. For example, if the motion perceived by the visual system conflicts with that perceived by other sensory systems there is a likelihood of motion sickness being induced. Reason and Brand [59] (as summarised by [5]) described there being two major categories of motion sickness, being derived from conflict between angular and linear vestibular systems (Canal-Otolith mismatch), and conflict between visual and vestibular systems (visual-vestibular mismatch).

The vestibular system (or inner ear) is essentially a human inertial motion sensor, able to detect rotational changes (equivalent to a gyroscope, sensed via the semicircular canals) and acceleration (equivalent to an accelerometer, sensed via the Otolith organs). This information is used alongside cues from the visual system and the somatosensory system (e.g. motor actions and proprioception) to determine a perception of self-motion. Reason and Brand suggested there were two types of conflict: type 1, where both systems signal contradictory motion information, and type 2, where one system signals motion whilst the other does not. The greater the discrepancy between the sensory information and the expected sensory information, the greater the chance of motion sickness occurring, and the greater the severity of the sickness [53, 5].

There are however other theories regarding the origins of motion sickness. The subjective vertical conflict theory [5] suggests that motion sickness arises from "situations where the determination of the subjective vertical, the internal representation of gravity, is challenged", meaning movements where the reference point of gravity changes, e.g. roll and pitch movements when seated, but not yaw movements (side-to-side). For example, "driving uphill at night along a winding road may provoke car sickness in the passengers in the back seat. The continuously changing gravitoinertial force vector, together with the inability of the semicircular canals to appropriately signal the angular motion because of the stable visual interior of the car... will subsequently provoke motion sickness." [5]. The ecological theory of motion sickness suggests that it occurs due to motion causing postural instability:

> "Animals become sick in situations in which they do not possess (or have not yet learned) strategies that are effective for the maintenance of postural stability (p. 195), and that postural instability... is necessary to produce symptoms" [60] from [8]

Indeed, studies have demonstrated that motion sickness can occur due to postural sway even without visual cues [54]. Postural sway has been considered as an indicator of the onset of motion sickness [12]. However, the fundamental causes of motion sickness are not yet fully understood, with suggestions that "an underlying central mechanism... driving both our posture and motion sickness symptoms" exists [8, 12].

Regardless of the underlying theory, it is well known that specific movements play significant roles in motion sickness. For example, Bles *et al.* noted that "linear acceleration and deceleration without appropriate view of the road ahead" induced sickness [5]. Lateral (bumps and undulations in a car ride) and vertical oscillations (at low frequencies, between 0.1 and 0.5Hz, peaking at 0.16Hz, e.g. the motion of a boat) both induce motion sickness [32]. The Coriolis or cross-coupling effect [30] is when nausea is provoked by head movements during yaw motion (i.e. where a conflict arises between the Canal-Otolith systems). Consider a car turning a corner, whilst a passenger additionally rotates their head. Depending on the directions of the rotation, the perceived rotational velocity may be very different to the actual rotational velocity. This is one of a number of effects experienced, particularly by pilots [55].

Finally, it is important to note that perception of motion is not uniform with respect to the field of view of the viewer:

> "Peripheral vision is relatively better at detecting motion than form. A moving object seen in the periphery is perceived as something moving, but it is more difficult to see what that something is... A person's ability to detect slow-moving stimuli decreases with eye eccentricity... For faster-moving stimuli, however, the ability to detect moving stimuli increases with eye eccentricity." [34] from [1] and [14]

Indeed, Keshavarz *et al.* [38] noted the impact of peripheral vision on perception of motion, showing that having peripheral vision of a projection screen displaying vehicle motion caused greater visually-induced motion sickness.

Occurrence and Prevalence

Motion sickness has three components: the characteristics of the stimulus, the susceptibility of the person, and the total time of exposure [59]. The result is that "anyone with a functional vestibular system can suffer from motion sickness, given the right prerequisites and if the exposure is continuous over a long period" [16] with studies showing that "virtually anyone with normal vestibular function when exposed to provocative physical body motion, disruption of vestibulo-ocular reflexes, or optokinetic stimulation can to some extent be made motion sick". [40]. Thus prevalence tends to be categorised by severity of affliction. It has been suggested that approximately one-third of the population are highly susceptible to motion sickness (becoming sick frequently when on any transport) ([49] from [40]), where ~5–10% of the population is extremely sensitive to motion sickness, ~5–15% relatively insensitive, and ~75% are subject to normal motion sickness (i.e. to a limited degree) [48], in line with observations based on the MSSQ-short motion sickness susceptibility questionnaire in a sample of 1711 members of the public [41].

Modes of transport, and their motions, also play a role in determining the severity of the experiences. All forms of transport create stimuli that will cause motion sickness for some given sufficient exposure. Seasickness typically has the most severe potential for sickness, given the strong stimuli involved, the length of exposure, and the frequent lack of matching visual stimuli, with one study reporting incidence on naval vessels of 62% [16]. For cars, passengers are particularly at-risk. For example, up to a quarter of co-drivers in rally cars were found to become motion sick if they were reading a book or sitting in the back seat [57]. But even public transport such as buses [29] or trains can cause significant problems [10, 13]. Generally, females [69] and children [31] have been shown to be more susceptible, with females showing greater variability in motion sickness over time than males [46, 42, 28].

Revisiting the sensory re-arrangement theory, consider a person suffering from motion sickness during a car journey. Their vestibular system can sense the accelerations/decelerations of the car being made by the driver, the lateral oscillations of the car resulting from a combination of the quality of the road and the ability of the driver, and the rotational changes made as the driver navigates and turns. Meanwhile, their visual system may or may not provide an awareness of motion (depending on the accessibility and visibility of external reference points such as the terrain, which can vary if the passenger decides to, say, read a book or is sitting in the back and unable to see out of the windows), and this awareness of motion may not align with what the vestibular system is suggesting regarding the magnitude of motion. Finally, other sensory capabilities (e.g. the somatosensory system) will only provide relevant feedback to the driver who is in control of the vehicle. Thus, there are many scenarios where sensory mismatches can occur, with motion sickness being the result.

The Future Of Motion Sickness In-Car

Car motion can be categorised as having lateral oscillations (rolls), rotational changes in direction (yaw), and vertical changes/oscillations (pitch), as well as accelerations/decelerations. These motions are influenced by the driver, and the road conditions, with the perception of these motions dictated by whether an individual is driving or is a passenger, where they are seated and what visual references of motion they are able to attend to. Of these, the primary contributor to motion sickness in cars is considered to be lateral oscillations (<0.5Hz) caused by variations in the road quality and driving style. This effect is compounded by seating position, with the rear seats increasing the magnitude of the oscillations [75].

The eventual adoption of autonomous cars is likely to change the primary contributor of motion sickness from oscillations to sensory mismatches. Firstly, it is feasible to suggest that the autonomous car could provide notice of actions [19], and drive in a style that minimizes oscillations, for example choosing high quality roads and gradual acceleration/decelerations.

Secondly, existing drivers will be freed from the driving task, reclaiming approximately 368 person hours per year spent by drivers in England alone [17]) for entertainment and productivity on-the-move, such as reading, working, consuming audio-visual media, gaming, etc. [67]. This would allow for the redesign of the internal environment of the car to better facilitate non-driving tasks (given that driving controls may be unnecessary) [21, 19], affecting both visual perception of motion and capability to anticipate motion. Indeed, proposals have been suggested to utilize the full space of the car for media consumption activities, such as a drop-down projector screen patented by Ford [15].

Thirdly, a network of autonomous cars could diminish car ownership and lead to increased incidence of car/ride sharing, guiding interior design toward privacy in a potentially shared resource [50]. This could lead to a greater variety of seating positions being utilized, with passengers in the rear more common, and seating becoming flexible and not necessarily front-oriented [20]. Consequently, a resurgence of interest in motion sickness treatments has been noted, specifically attributed to the use of displays in cars (termed *nauseogenic visual displays* [27]). Thus, whilst an autonomous vehicle might work to minimize motion sickness-inducing oscillations, the passengers may well undermine this effort by inducing motion sickness through their activities [20].

Mitigations, Treatments and Recovery

With respect to car travel specifically, minimizing lateral oscillations (e.g. reducing accelerations[75]) is effective [18]. Drivers have been shown to avoid motion sickness because of their engagement with other sensory systems (e.g. proprioceptive feedback) and their control of the motion aiding anticipatory actions. For example, lateral oscillation-based motion sickness is avoided through prediction of the oscillations as they depend upon the driving behaviour, which in turn allows for compensatory actions such as tilting the head [3, 27, 63]. When applied to passengers, this foreknowledge can diminish perceived motion sickness [78, 21].

For accelerations/decelerations and rotational movements, providing an artificial horizon can reduce motion sickness [74]. Bles *et al.* [5] suggested that this was due to "the fact that seeing the horizon helps to keep the sensed and subjective vertical aligned", framing this within their subjective vertical conflict theory. Stability has also been shown to diminish motion sickness, through aligning the body with changes in the environment [26, 27] and minimizing head movements [4]. As previously discussed, a growing body of evidence has suggested that postural stability, or lack thereof, can play a significant role in determining the severity of motion sickness [12]. Regarding longer-term approaches, habituation (providing sufficient exposure for adaptation to occur) is the primary means of treating motion sickness. However, "5% of the population never adapts to motion sickness triggering stimuli, given a fully functional vestibular system" [16], whilst the duration of car journeys, and overcoming initial sickness, may prevent habituation. Pharmacological approaches can be problematic in terms of effectiveness, availability and cost, and may have a negative affect on concentration. Behavioural approaches, such as controlled breathing or listening to calming music [84], can provide relief, but require that the individual devote focus on that activity rather than work or play.

Regarding recovery from motion sickness, there are three factors: sensitivity to stimulation, the rate of adaptation to stimulation, and the time constant of the decay of the elicited symptoms [40]. However, much as with the factors that induce motion sickness, there is a high degree of variability in each of these recovery factors, with "the decay of symptoms vary[ing] enormously across individuals... by 100-1" [40].

Vection & Visually Induced Motion Sickness In VR

When considering VR HMDs in-motion, visually perceived motion must be considered. Vection is often described as "illusory self-motion" [39]. This illusion of self-motion, in the absence of any congruent physically perceived motion, is primarily the cause of Visually Induced Motion Sickness (VIMS), often a significant component of simulator sickness / cybersickness [39]. For example, if the VR HMD wearer is stationary yet visually perceives their avatar walking or running through a virtual environment, this would have the potential to induce VIMS.

The problem of vection has been tackled in a number of ways, most pertinently by Fernandes and Feiner [22], who manipulated the visibility of mid-peripheral motion cues, resulting in decreased VIMS. As discussed , disparity between what is visually and physically perceived is likely to induce motion sickness, and VR HMD use in-motion offers up new ways in which this disparity might occur:

Motion sickness / inverse vection An illusion of stability where the VR user may physically perceive motion whilst visually perceiving a stable virtual environment;

Contradictory vection An illusion of self-motion conveyed through VR that contradicts perceived physical motion, e.g. moving left in VR whilst turning right in the car;

Magnitude of vection A portrayal of self-motion which matches the physically perceived motion but at a different magnitude, e.g. perceiving a car acceleration as a small, subtle movement instead of as absolute velocity, or increasing the visual magnitude of the acceleration to exhilarate.

Each of these disparities is likely to be compounded by the amount and type of movements performed by the VR user, e.g. viewing content which requires constant and rapid changes in gaze orientation, compared to content which is stable or whose orientation or position is physically manipulated by the user (e.g. reading a book, or physically grabbing and moving the world [47]). Thus, careful consideration must be given as to what particular form of motion conflict is examined, and how it is physically enacted.

Existing Support For VR HMD Use In-Motion

There has been little recent work looking at VR HMD use in-motion with the current generation of consumer headsets. Soyka *et al.* [73] as part of the *VR-Hyperspace* project examined the effect of turbulent motions on VR HMD users in a flight simulator, using an Oculus Rift DK 1 to prototype VR use as an aeroplane passenger as part of an examination of future entertainment options in-flight. They evaluated turbulence/oscillations through three turbulent episodes of 10 seconds, in two virtual motion environments: a virtual aeroplane and a magic carpet ride over tropical islands. They found that "brief exposure to turbulent motions [do] not get participants sick". Indeed, VR HMDs have seen recent deployment in real-world flights as standard, most notably by Qantas[64]. Once the plane is up to speed there are few turns or changes in acceleration to cause perception problems.

Currently, VR HMDs are heavily reliant on high frequency, low latency inertial measurement units (IMUs) to accurately track the wearer's head to provide dynamically updating displays. This is the case for both existing mobile HMDs (e.g. the Samsung Gear VR, which supports rotational movement only) and PC-based headsets (e.g. positionally tracked devices such as the HTC Vive and Oculus Rift). Gyroscopes are typically used as part of a sensor fusion approach, alongside accelerometers and magnetometers for accurate 3 DOF rotational tracking, external beacons and/or cameras for 6 DOF positional tracking [2], to track the movement of the headset.

This reliance on gyroscopes means that when used in-motion, viewing is influenced by orientation changes caused by transportation (e.g. a car turning a corner), which is interpreted in the same way as the user turning their head. This is a result of the current focus on delivering accurate, low latency tracking in stationary environments. However, positionally-tracked VR HMDs will in the future be able to maintain stable viewing in-motion, meaning the VR view of the world need only react to movement by the user, and not the vehicle. This can already be seen in highly controlled scenarios, where the external motion of the VR HMD is known in advance, such as in the case of VR rollercoasters where users experience synchronized virtual and physical representations of the ride [77]. Consequently, both existing VR HMDs (which interpret vehicle movements as head movements) and future positionally-tracked VR HMDs (which could ignore external movements) merit consideration with respect to sickness incidence in-motion.

Outcomes From Literature Review

Users of VR HMDs in motion, engaging in interactive environments where their visual perception of motion may not be aligned with their physically perceived motion, may exhibit some degree of motion sickness. This is likely to make HMDs very difficult to use in cars for many people and thus the benefits offered by autonomous vehicles cannot be taken advantage of. Given this, the first problem we investigated was motion sickness incidence due to VR HMD use in-motion to provide a baseline, which is missing from the literature. Specifically, we looked at both VR HMDs that interpret the turning of a vehicle as part of the user's head movement, and future VR HMDs that have a stable frame of reference with respect to vehicle movement. We then examined how motion cues could be delivered to users in combination with a virtual environment, utilizing the sensitivity of peripheral vision, to see what effect this might have on motion sickness and immersion. In this way, we aimed to provide a general solution for sensory conflict that could be used for any static VR content.

STUDY: IN-CAR VR HMD USE IN-MOTION

We examined the use of VR HMDs in-motion through an in-car study of passengers wearing VR HMDs watching 360° VR video content as they were driven around a city. We could recreate an ecologically valid driving experience, of particular relevance to autonomous cars and public transport, and examine the effects of real-world motion cues, specifically rotations and accelerations/decelerations, over a set route. Our aims were to examine:

- VR HMDs where all rotations affect VR viewing orientation, regardless of whether they occurred through user head movements or vehicle motion;
- Future positionally-tracked VR HMDs that can compensate, correct for or ignore external vehicle rotation;
- The utility of peripheral visual motion cues to give some sense of external vehicle motion.

Six conditions were defined. They evaluated the effect of providing a stable VR view relative to car motion (contrasting current VR HMDs in-motion and future VR HMDs that could ignore vehicle motion), and of re-incorporating some perception of vehicle motion through mid-peripheral vision. There were two baselines: ((1) VR video and (2) motion only), an additional Condition (3) to test the accuracy of our motion cues, and three Conditions (4–6) to examine these effects (V=Video, M=Motion)[1]:

1: VR Video Baseline simulator sickness. Users were stationary, wearing a VR HMD, watching 360° video. This was to get a baseline for standard simulator sickness;

2: Motion Only Baseline motion sickness. Users were in motion but not watching VR. This gave a baseline for motion sickness from just being driven in a car;

3: VR Motion Environment In-motion, wearing a VR HMD. The motion of the car was synchronously portrayed in VR, with the HMD user perceiving themselves moving through a basic landscape. This was to evaluate whether our sensing of motion matched what was physically perceived;

4: VR V+M In-motion, wearing a VR HMD, with all rotations (head movements and vehicle rotations) interpreted as head movements. **This conveyed turning of the car**;

5: VR V+M with compensation In-motion, wearing a VR HMD, with compensatory rotations of the video counteracting vehicle rotations. This provided a stable view in VR, **conveying no vehicle motion**;

6: VR V+M with peripheral feedback As Condition 5, with compensatory rotations of the video counteracting vehicle rotations, but with the motion environment of Condition 3 blended into the peripheral ±10° of the VR view. This was to evaluate the effectiveness of presenting motion cues mid-peripherally alongside existing VR content. **This conveyed turning and acceleration peripherally**.

Implementation

For the VR HMD, we used a Samsung Gear VR mobile HMD (SM-R322, 310 grams, 96° FOV, see Figure 1) paired with a Samsung S7 smartphone (VR framework version 11, service version 2.4.29, 60Hz). To have the capability to both convey the motions of the car in VR, and counteract the rotations of the car, a Nexus 5 smartphone was used. It was mounted to the car, with its gyroscope (sampled at 30Hz at a latency of ~40ms) providing bearing changes. It was also paired with an OBD2 device (OBDLink LX [72], ~14Hz at a latency of 100ms) for capturing car velocity in real-time. For communicating the car motion to the HMD, we used a SocketIO server over which both the Nexus 5 and S7-powered HMD communicated. The study was conducted in a 2015 model Vauxhall Insignia, chosen both to minimize oscillations (through a modern suspension system) and provide a fast OBD2 link.

[1]To see how conditions operated in-motion, view the attached video.

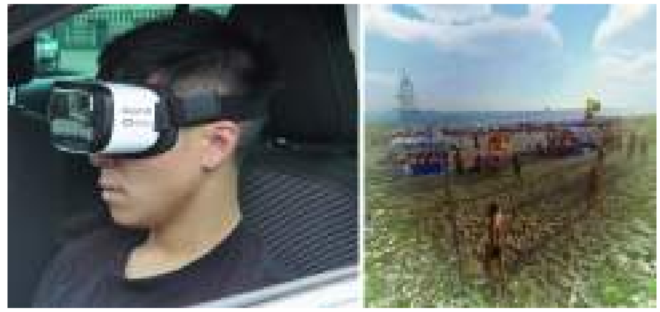

Figure 1. Left: Gear VR HMD used in study. Right: Peripheral blending of Condition 6, combining motion landscape and 360° video.

There were three software elements. Firstly, we created a motion environment synchronized to the car motion. An initial gyroscope bearing was taken with users looking straight ahead whilst wearing the headset. Subsequent changes in this bearing determined the direction of the forward vector in the motion environment, with velocity also portrayed. Secondly, we stabilized the VR view with respect to car motion. Given the black box sensor fusion of the VR HMD tracking, we chose to exploit the fact that 360° VR video is typically rendered on a sphere, using gyroscope readings to perform counter-rotations of the sphere. Pilot testing showed that readings taken every second frame, combined with linear interpolation to smooth transitions, provided the most comfortable and accurate counter-rotation, accounting for variance in the gyroscope readings. Thirdly, we blended the stabilized video content and the motion environment for the peripheral motion cues. For this we used a shader effect combined with raycasting to determine the current video fixation point, with alpha blending to combine the motion environment and the video.

It is important to note that this approach, whilst suited to a prototype system, had some drawbacks regarding gyroscope drift. A gyroscope is subject to drift over time and motion. In the case of the Gear VR, a combination of gyroscope, accelerometer and magnetometer are used to retain a relatively accurate bearing. However, magnetometer readings are unreliable in-motion, due to variances in the magnetic field and the environment. Thus, it was inevitable that drift would occur. We designed a mechanism to allow users to re-orient the system, taking a new bearing for the forward vector and resetting the Gear VR tracking. To do this, users interacted with the Gear VR touchpad, located on the right side of the headset. If any desynchronization was perceived, they were to look straight ahead and swipe downwards. The VR view then faded out and back in over the course of 2 seconds.

Demographics and Pre-Screening
Eighteen males (18<age<35) were recruited from University mailing lists/forums (mean age=25.1, SD=4.7). They were pre-screened on motion sickness susceptibility using MSSQ-Short [25] with selection based on having, at worst, only moderate susceptibility (all participants in the 75th%ile MSSQ with majority in the 50th%ile of slightly susceptible or less). This level was chosen as we did not have an understanding of the magnitude of the sickness effects of VR HMD use in motion and thus could not ethically examine more susceptible participants at this point. Participants were asked not to take anti-motion sickness medications, antihistamines, or alcohol immediately prior to the experiment, and to abstain from eating for at least an hour prior.

Measures and Experimental Design
For measuring motion sickness, during each condition we used a standard 7-point illness rating scale from [29] where the extreme indicated the participant was experiencing moderate nausea and wished to stop, at which point they would inform the experimenter and the condition would be stopped prematurely. Changes were indicated in real-time by participants using forward and backward swipes of the Gear VR touchpad, which would temporarily present the scale over the VR content. The Simulator Sickness Questionnaire (SSQ) [36] was used after each condition to measure both motion and simulator sickness, and duration was noted in the event of prematurely stopping a condition due to sudden onset of illness, or reaching the maximum point on the illness rating scale. Physiological measures were ruled out, as they are both weakly correlated with motion sickness [70], and their use would be confounded by other factors (e.g. immersion, excitation due to unexpected movements). For measuring presence, the iGroup Presence Questionnaire (IPQ) [68] was used. Finally, users were asked to rank the VR Video In-Motion conditions (4–6) in order of preference, before taking part in a short interview.

The experimental design was heavily influenced by pilot testing regarding both duration and ordering. Typically, motion sickness studies last for in excess of 15 minutes [5]. They are often conducted with extreme stimuli to provoke significant sickness effects [7]. However, these durations were problematic for our study given the unknown magnitude of sickness effects of VR HMD-use in motion. Instead, we evaluated each condition for 10 minutes of standard city driving and gave plenty of rest time between conditions. To provide consistent and ecologically valid motion stimuli, laps of a quiet, predominantly one-way road system with no traffic lights were undertaken. The acceleration profile can be seen in Figure 2. Each lap took ~2 minutes and featured 4 places where notable accelerations and decelerations occurred, meaning that each condition consisted of ~5–6 laps. Conditions started and ended at the entrance to a public park, allowing participants to leave the car for recovery, if required.

Through pilot testing, we determined that two separate ~1hr:15min sessions, with 3 conditions per session were sufficient to allow for both experimentation and as much recovery time as required by participants. The exception to this was Condition 5 (VR V+M w/ compensation), which was particularly problematic with respect to sickness and recovery time, with a high likelihood that participants would be unable to continue. Accordingly, this condition was evaluated last. The first session was counter-balanced for Conditions 3, 4 and 6. The second session evaluated the baselines (Conditions 1 and 2), again counter-balanced, and then finally Condition 5. Three VR video clips were used, chosen on the basis of containing no movement, portraying stationary events in 360° [51, 62, 79], and played in the same order for every condition.

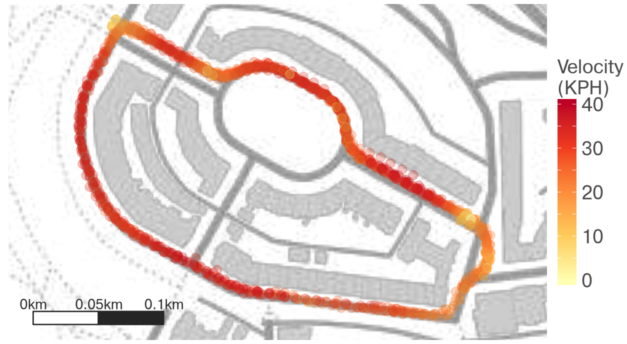

Figure 2. 0.86km test route velocity profile, as captured throughout the study across participants using GPS and OBD2 velocity.

RESULTS
Unless otherwise stated, for parametric tests a repeated measures ANOVA was performed using *lme()* in *R* as prescribed by [23], with likelihood ratios reported, and *post hoc* Tukey contrasts performed where applicable. For non-parametric tests (denoted NP) a Friedman's ANOVA was performed using *friedman.test()* in *R*, with *post hoc* pairwise Wilcoxon Rank Sum Tests performed where applicable.

Duration of Usage and Perception Of Motion
All of the VR in-motion conditions featured some early stoppages due to feelings of nausea, predominantly toward the end, as reflected in the mean duration of each condition, see Table 2. There were no statistical differences in terms of the subjective perceptions of rotations or motion, but the peripheral blending of Condition 6 significantly diminished participants' sense of acceleration. In general, perception of motion was not rated highly, indicating that rotations and accelerations alone do not convey the full breadth of experienced motion. The lack of positional tracking of the GearVR meant that oscillations (e.g. uneven roads) and positional movements (e.g. leaning forward or backward based on accelerations) were not incorporated into the visual representation of motion.

Sickness and Presence
Sickness on the SSQ scales showed a statistically significant increase in all the VR in-motion conditions compared to both baseline simulator and motion sickness, but there were no significant differences between the VR in-motion conditions. Mean presence (IPQ score) remained unaffected by the motion of the car and the means by which this motion was incorporated. The generally low presence scores suggest this metric was confounded by the relatively low presence of the Gear VR HMD and the 360° video content.

Rankings Against Susceptibility, Sickness & Presence

Broadly, there was little to discriminate between the in-motion conditions. However, user rankings (see Table 1) revealed differing preferences, with half of participants preferring some form of conveyance of motion. Examining motion sickness susceptibility scores against preferences hints at these preferences being aligned with susceptibility, as seen in Figure 3. An ANOVA on susceptibility scores showed a significant difference $F(2,15) = 4.12, p < 0.05$ on user preference, with *post-hoc* Tukey showing differences between preferring Conditions 4–6 ($p < 0.05$) but not 5–6 ($p = 0.09$) or 4–5 ($p = 0.69$), suggesting that those that preferred the peripheral blending condition featured a greater susceptibility to motion sickness.

Metric	4 VR Video+Motion	5 VR V+M w/compensation	6 VR V+M w/peripheral feedback
User preferences	4 (22%)	8 (44%)	6 (33%)
Excluding (4)	–	9 (50%)	9 (50%)

Table 1. Total of preferred conditions, and preferred conditions excluding (4) by taking second preferences.

Examining the real-time illness rating (Figure 4), we see how preferences were influenced by perceived sickness. For those that preferred Condition 4 (VR Video+Motion, with the view rotating as the car turned), the stabilized view of Condition 5 led to a steady and continual increase in sickness. Whilst this was somewhat diminished by the peripheral cues of Condition 6, the more overt presentation of rotation in Condition 4 was best suited to this group and matched their inherent motion sickness. For those that preferred Condition 5 (VR V+M w/ Compensation, with the rotations of the car not affecting viewing), the visual perception of motion in Conditions 4/6 appeared to make their symptoms worse, especially the combination of visual cues of Condition 6. With these participants,

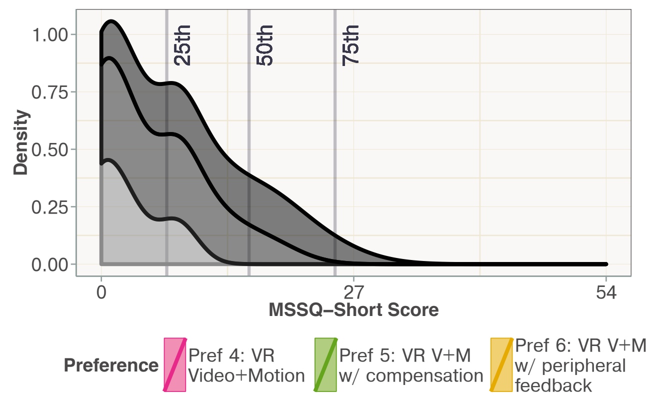

Figure 3. Stacked density plot (*geom_density* in R, using ..count.. and "stack") of motion sickness susceptibility against preferred condition (higher is more susceptible), with labels indicating susceptibility percentiles for the general population from [41]. 50th%ile is considered "slightly susceptible", and 75th%ile "moderately susceptible".

their sickness was minimized by not presenting motion. It appears that these individuals are particularly susceptible to visual discrepancies in motion, suggesting that our conveyance of motion was insufficiently synchronized, or that perceiving different conflicting cues is particularly problematic for them. For those that preferred Condition 6 (VR V+M w/ Peripheral Feedback), the peripheral cues appeared to slow the onset of sickness, however all conditions provoked a consistent level of sickness throughout.

Examining SSQ total sickness against first preference and Condition, a two-factor ANOVA showed no main effects on Condition ($p = 0.37$) or preference ($p = 0.54$), but a significant interaction effect ($F(4,30) = 5.65, p < 0.01$), with contrasts showing an effect on Condition 4 versus 5 against preference for Condition 4 versus 5 ($b = -12.02, t(30) = -4.08, p < 0.01$), which can be seen in Figure 5. There was no significant con-

Metric	1 VR Video	2 Motion Only	3 VR Motion Env.	4 VR Video+Motion	5 VR V+M w/ Compensation	6 VR V+M w/ Peripheral Feedback	RM-Anova	Tukey *Post-hoc*
Mean Duration (sec)	600.0 (0.0)	600.0 (0.0)	569.9 (122.9)	563.5 (118.5)	567.2 (96.8)	555.4 (95.6)	$\chi^2(5) = 8.99, p = 0.1$	NA
Total Stopped early	0	0	2	3	3	5	$\chi^2(5) = 12.9, p < 0.05$	1-6, 2-6
IPQ Score	3.5 (0.9)	–	–	3.6 (0.9)	3.3 (0.9)	3.4 (0.8)	$\chi^2(3) = 2.54, p = 0.47$	NA
SSQ.N Nausea	9.0 (15.6)	8.5 (14.6)	39.2 (29.8)	53.5 (52.4)	58.8 (49.9)	60.4 (49.7)	$\chi^2(5) = 49.59, p < 0.01$	1-{3,4,5,6}, 2-{3,4,5,6}
SSQ.O Oculomotor	12.9 (16.5)	3.4 (9.1)	35.0 (28.0)	37.9 (33.7)	43.0 (37.3)	43.4 (35.3)	$\chi^2(5) = 51.83, p < 0.01$	1-{3,4,5,6}, 2-{3,4,5,6}
SSQ.D Disorientation	13.1 (26.3)	6.2 (10.9)	57.2 (62.4)	62.6 (71.5)	71.9 (72.1)	72.7 (71.4)	$\chi^2(5) = 44.8, p < 0.01$	1-{3,4,5,6}, 2-{3,4,5,6}
SSQ.TS Total Score	6.2 (10.4)	3.0 (5.0)	24.1 (23.1)	27.4 (28.6)	31.2 (28.9)	31.6 (28.0)	$\chi^2(5) = 49.80, p < 0.01$	1-{3,4,5,6}, 2-{3,4,5,6}
Rotation (NP)	–	–	4.1 (1.1)	3.9 (1.8)	–	3.3 (1.7)	$\chi^2(2) = 1.4, p = 0.5$	NA
Motion (NP)	–	–	4.1 (1.2)	–	–	3.4 (1.8)	$\chi^2(1) = 1.6, p = 0.2$	NA
Acceleration (NP)	–	–	4.5 (1.0)	–	–	3.4 (1.5)	$\chi^2(1) = 12, p < 0.01$	NA

Table 2. Statistics and questionnaire results. IPQ score 0–6, higher is more presence; SSQ score higher is more sickness (max 235); Ranking lower is better; Rotation/Motion/Acceleration 0–6 from strongly disagree to strongly agree that visual and physical motion cues were aligned. Green denotes $p < 0.05$, NP denotes non-parametric tests.

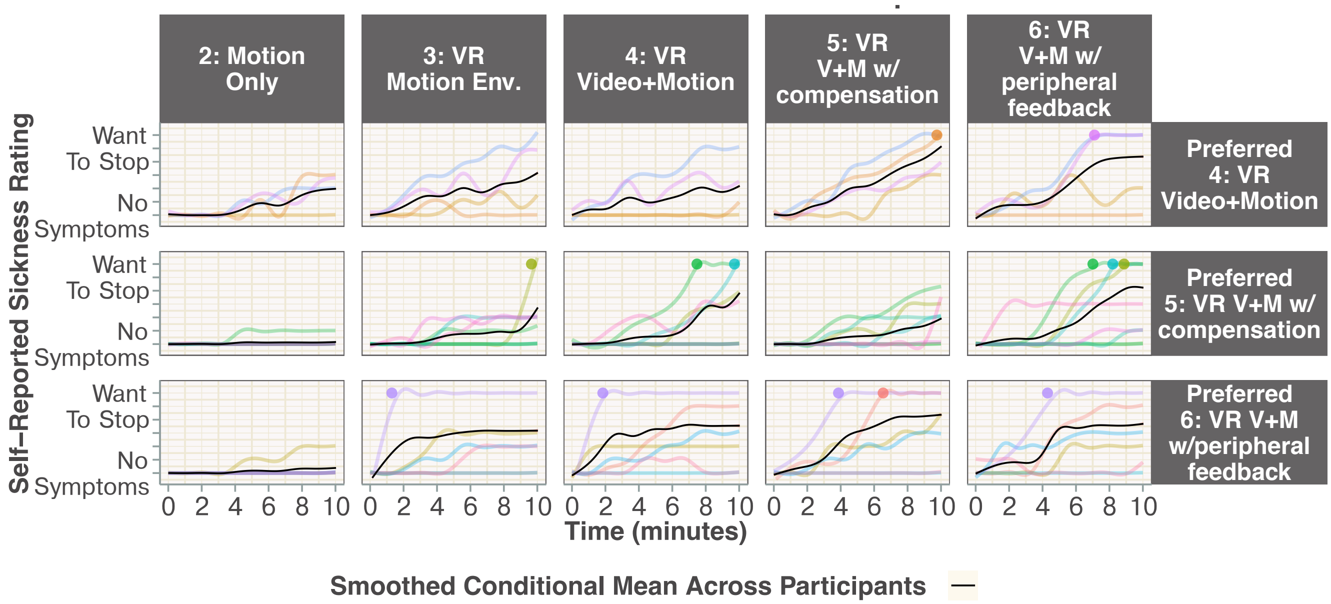

Figure 4. Plot of smoothed conditional mean real-time sickness ratings against condition and preference across participants (in black), with individual participants plotted (in colour) and if they stopped the condition prematurely (coloured circles show time stopped).

trast between Condition 5/6 against preference for Condition 5/6 ($b = -4.99, t(30) = -1.88, p = 0.06$). However, the interaction plot suggests a similar trend to that demonstrated in Figure 3, with sickness being in-part minimized by preference.

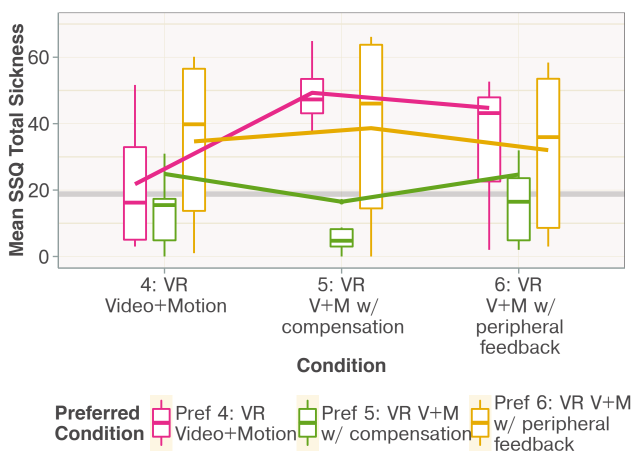

Figure 5. Interaction plot of SSQ total sickness score against condition and preference (higher is worse). Boxplots indicate the first and third quartiles (25th and 75th percentiles). Coloured lines indicate means. Grey background line indicates the sickness score of the *2F64C* flight simulator, suggested as indicating a problematic level of sickness [37].

Examining IPQ presence in VR against preference and Condition, a two-factor ANOVA showed no effect of Condition ($p = 0.33$) but a significant effect of preference ($F(2,15) = 4.8, p < 0.05$) with no interaction ($p = 0.52$). *Post-hoc* Tukey tests showed higher mean presence scores for those preferring Condition 4 versus Condition 6 ($p < 0.05$), but not 4–5 ($p = 0.69$) or 6–5 ($p = 0.09$).

Interviews

Interviews were loosely guided on the basis of reported preferences. Interviews were coded using Initial Coding, where participants' statements were assigned emergent codes over repeated cycles. These codes were then grouped using a thematic approach and reported based on frequency and interest (see [66]), with representative excerpts quoted.

Incorporating Rotations Of The Car "Like A Tour"

Six participants commented on the fact that Condition 4, where the view rotated with the car, aided exploration whilst feeling natural, allowing them to explore beyond the physical viewing constraints of the headset:

> *P1*: It was interesting because I saw stuff which would normally be behind me. You can look around in the car with the headset on, but it takes quite a lot of effort to see what's directly behind you.
> *P8*: Despite the car moving and shifting your perspective, it felt more like I'm in a cinema and... the camera is panning and focusing my attention on other things.

Conversely, 6 participants said they did not appreciate the "lack of control" (P11), noting "it was quite annoying if you were trying to focus on something and obviously the car is turning away" (P6). Attempting to compensate for this motion to continue looking at a particular point of focus caused one participant (P14) to note an onset of sickness.

Providing No Motion Cues Is Dichotomous

For 5 participants, Condition 5 was preferred because it allowed for more control over their viewing, which was in one case noted as "worth the slight discomfort" in comparison to other conditions (P9). However, 6 participants reported an intolerance to this lack of motion presentation:

> *P3*: I think the feeling was more intense compared to the others. I felt the stomach effect more in this particular one than the rest of them.
> *P14*: I could just tell that this was going to make me ill quite quickly... it was more immersive almost, but it just meant that especially if you were going faster or when there were bumps mid turns... I knew I was getting there with that one.

Peripheral Motion Provides Comfort For Some

For Condition 6, three participants specifically noted that perceiving peripheral motion provided comfort, with 7 participants noting some preference for peripheral cues:

> *P8*: You're very much aware that OK we are moving, we are turning, I'm very aware of what the car is doing. It's slightly comforting, because you have this sort of experience and feedback because you still have this contact with the real world.
> *P11*: The mixed image of the motion and video felt more comfortable. I could feel motion and I knew that there was motion happening in the vision, it made sense.
> *P14*: The peripheral one I thought was the best because it showed where I was going... I felt the least sick in this one, but then it wasn't quite as immersive... but I think having something in the visual field was better.

However, 6 participants noted that the peripheral cues either distracted from their immersion or were felt to be unnecessary. In 3 cases it made it difficult to focus on the VR content, whilst for 2 participants it provoked more nausea through the conflict of visual imagery. In addition, 2 participants noted that they struggled to or did not perceive the peripheral cues:

> *P6*: I preferred with no peripheral view because you can just focus purely on the video. Having the edges visible on the screen is just a distraction for no good reason.
> *P10*: My nausea felt more severe, the motion combined with the static images of the video maybe enhanced that somehow.

Discontinuities Are Disruptive

Two users noted that discontinuities between the VR motion environment and their perception of the physical world were particularly off-putting, with the VR content not adequately reflecting the changing environment around them:

> *P6*: When the sun did hit me, that was a bit confusing. The sun came out after I put the headset on, so I didn't actually realize there was going to be warm sunlight hitting my body.
> *P9*: It was a really strange disconnect between an overcast sky [in VR] and feeling sunlight on my skin. You start looking around subconsciously for the sun, and when you go behind a tree and there's no difference in temperature, you don't feel yourself going into the shade.

DISCUSSION

Our experimental conditions set a baseline for future work as they demonstrate, for the first time, the differences in motion sickness levels between seated VR and use in-car and in-motion. We also showed the effects of different visual presentations of motion on users, which we will now discuss.

No Universally Suitable Visual Portrayal of Motion

The results indicate that there was no universal solution for minimizing sickness. We evaluated three VR in-motion conditions: (4) conveyed rotations only, (5) conveyed no motion and (6) peripherally conveyed rotations and accelerations. Examining motion sickness susceptibility, perceived sickness, presence and real-time illness revealed few differences between conditions over the 18 participants. However, breaking these results down by preference suggests that different presentations may be required by different subsets of passengers, with the wrong type actually making people feel worse.

Preference For Conveyance Of Motion Was A Dichotomy

Preferences were split between conditions, with 4 participants preferring Condition 4, 8 preferring Condition 5 and 6 preferring Condition 6. Conveying rotations through Condition 4 confused matters somewhat, as these preferences were in-part based on the capability of this condition to allow for more exploration, with the view of the VR scene moving with the car. Excluding (4) and taking second preferences (see Table 1), half the participants preferred some presentation of motion, and half did not. This preference did not entirely align with susceptibility, sickness or immersion. However, for those with a higher susceptibility to motion sickness, peripheral conveyance of motion was in-part preferred, with feedback suggesting that peripheral presentation provided support.

VR That Ignores External Motion Was Useable For Some

For those that preferred the view of Condition 5, which compensated for the turns of the car, sickness scores were typically below the threshold given by Kennedy *et al.* [37] that denotes a level of sickness deemed problematic for simulator use. This suggests that, given a VR HMD that can counteract vehicle rotations, for these users VR in-motion is useable (albeit for the short duration examined). For these users, conveying or integrating motion into their experience appeared to increase their sickness, being both unnecessary, distracting and potentially introducing a subtle discrepancy in perceived motion to which these individuals were particularly attuned.

VR In-Motion Was Problematic For Many

For the majority of participants, sickness exceeded what would be considered acceptable for a motion simulator [37]. Our results demonstrate that there are significant problems regarding VR HMD use in-motion that need to be overcome to make VR in-motion usable for the general population.

Limitations and Guidelines For Further Experimentation

Our use of a compensatory gyroscope will have led to additional visual discrepancy, meaning it is possible that sickness was over-reported. The latency of the gyroscope and OBD2 link, the gyroscopic drift (~20° per min), the necessity for user resets of the forward vector (~once per lap, mean=4.9, SD=2.4) and the lack of conveyance of oscillations could all contribute to a, likely modest, increase in sickness. Consequently, we recommend that VR HMDs supporting positional tracking be used in-motion if possible. This would provide an accurate forward vector for car motion, as well as allow the conveyance of oscillations, a component of motion sickness we were unable to evaluate. Whilst other implementations could be considered (e.g. GPS and gyroscope, periodic resets of orientation, marker tracking), some form of positional tracking appears preferable. Problematically, consumer HMDs with positional tracking currently fuse both optical tracking and IMU data, meaning there is a reliance on gyroscopes which would make their immediate deployment in-car difficult.

There are also a number of factors upon which sickness is likely to vary that must be accounted for e.g. duration of stimulii; the effectiveness of interventions over time; characteristics of the route, vehicle and motion experienced; different forms of vection (see Section 2.2); differing motion and simulator sickness susceptibilities; the specifications of the HMD; age and user demographics; and the virtual content being experienced. For example, manipulating the workload demands of virtual content would be likely to have an impact, given that mental distraction has been shown to decrease sickness [9]). Future studies should consider these factors to determine whether our approach (e.g. a narrow demographic and a controlled real-world route) is suitable.

Evaluating VR in-car is also ethically challenging. Due to ethical and resource constraints, we evaluated multiple conditions per session, for durations of 10 minutes at a time (given the unknown magnitude of sickness that would be induced). Whilst counter-balancing was employed, and participants were given significant recovery breaks between conditions, there may be cumulative effects across a session. This design was acceptable given we were examining low-susceptibility individuals, however for a broader population, we would evaluate one condition per session over multiple days to rule out cumulative effects and allow for increased exposure time.

RECOMMENDATIONS FOR FURTHER RESEARCH

Peripheral Blending and Other Presentation Techniques

With respect to direct extensions of this study, peripheral blending of motion shows some promise for susceptible individuals. However, this implementation was limited by the technology. The Gear VR HMD has a field of view (FOV) of ~96°; of this, our peripheral display took over $\pm 10°$ from the edge. Whilst this is peripheral with respect to the HMD, this is not fully peripheral with respect to our visual field. Consequently, any expansion in VR FOV (e.g. HMDs with high FOV lenses [82] or sparse peripheral displays [83]) would allow for further exploration of the effectiveness of conveying motion through the mid-to-far periphery of the eye.

We used a basic VR landscape to portray motion to maintain 60Hz when rendered in conjunction with video content. Higher fidelity portrayals (e.g. based on real surroundings with discernible landmarks), or abstract cues (e.g. using environmental or shader effects to portray motion) could prove effective. Motion could be incorporated implicitly into VR (as with the Gear VR and Condition 4), by design (as part of a game), or generically for any content (e.g. peripheral blending) and could be incorporated dynamically based on the perceived sickness of the user. The magnitude of this presentation of real world motion could also be manipulated, with subtle conveyances potentially effective, for example visually perceiving small movements on the basis of larger accelerations and decelerations. Given foreknowledge of the route, motion could also be conveyed only when it occurs, for example showing a motion landscape for the duration of the car turning, or viewing could be restricted temporarily [22]. Initial user calibration will also be required to determine susceptibility and choose the best method of VR presentation.

Anticipatory Cues and Provoking Anticipatory Actions

Our literature review suggested a number of promising avenues. Firstly, having an understanding of impending motion might help users to compensate for, and anticipate, changes in velocity and acceleration. Manipulating the VR view to induce anticipatory actions might also help prevent motion sickness. In tilting trains it has been noted that "if head roll was initiated before the lateral acceleration, there was no motion sickness" [3, 35]. Asking car passengers to mimic the driver's head movements has noted a similar effect [3, 78]. As an example, a VR display that tilted content so users had to match the tilt to continue reading might mimic these results. Similarly, the conveyance and magnitude of oscillations could be altered in VR. Such effects might make VR HMDs, and notably also AR HMDs, ideally suited to facilitating entertainment and work whilst preventing motion sickness in autonomous cars and other transportation, where the environment might lead to sensory conflict and consequently motion sickness [20].

Vestibular Counter-Stimulation

Mitigations are also not limited to visual cues [27]. For example, Galvanic Vestibular Stimulation (GVS) [11] has the capability to alter our physical perception of motion and has been applied to the problem of vection [56], whilst other devices (e.g. inducing physically inducing vibrations) have also been suggested [7]. These could be used to counteract physically perceived motion. However, there are still significant difficulties to overcome regarding the practicality of delivery, adoption and effectiveness in the general population.

Social Acceptability And Safety

Willingness to use VR HMDs in-motion must be considered. For private spaces such as cars, provided there is sufficient trust [65] in the vehicle, then VR HMD use is more straightforward. However, for public transport, social acceptability, and issues of personal space and safety may inhibit adoption [61]. McGill *et al.* have begun to look at ways of bringing people into the VR world to address some of these issues [44, 6, 45]. AR HMDs may be more acceptable here and research into solutions across mixed-reality HMDs should be investigated.

CONCLUSIONS

As cars become autonomous, more passengers will need to fill more time on journeys. One way to do this is with VR and AR HMDs. These headsets have the potential to allow passengers to virtually escape the confines of their vehicle. Instead, they might spend their time in a virtual cinema with friends at-a-distance [45], or a virtual office, making more entertaining and productive use of travel time. However, a key drawback is motion sickness.

Given this motivation, this paper has, for the first time, examined the usability of VR HMDs in-car. Through an on-the-road study, we have established the extent to which motion sickness represents an obstacle to such usage in real world conditions. We have also examined how motion sickness can be diminished through differing visual presentations of motion in VR, aimed at minimizing sensory conflict. We found that there is no one best presentation with respect to sickness and immersion, with differently susceptible groups requiring different solutions, be they conveyance of rotations, peripheral conveyance of motion, or no conveyance of motion at all. Finally, based on both our results and the existing literature, we give suggestions for further experimentation, and describe what new research is required to arrive at AR and VR HMDs that are usable in-motion, providing an entry point for HCI to contribute to this problem. Our results suggest that there is, as-yet, no universal solution for minimizing sickness from VR HMD use in-motion, however we have begun to explore how different solutions can make VR HMDs usable in transit.

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