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

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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

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,

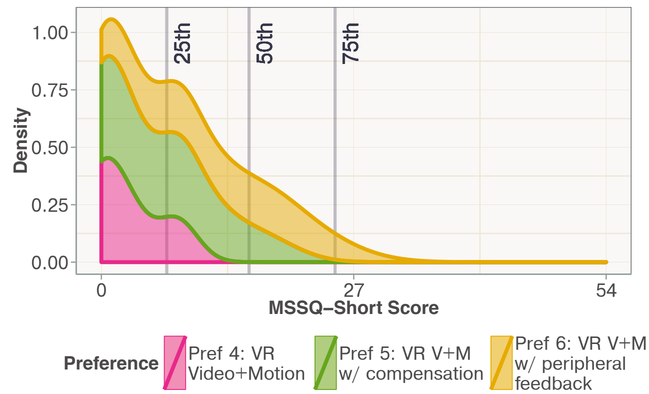

Figure 3. Stacked density plot (*geom_density* in R, using ..count.. and "stack") of motion sickness susceptibility against preferred condition (higher is more susceptible), with labels indicating susceptibility percentiles for the general population from [41]. 50th%ile is considered "slightly susceptible",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