From *Slow-Mo* to *Ludicrous Speed*: Comfortably Manipulating the Perception of Linear In-Car VR Motion Through Vehicular Translational Gain and Attenuation

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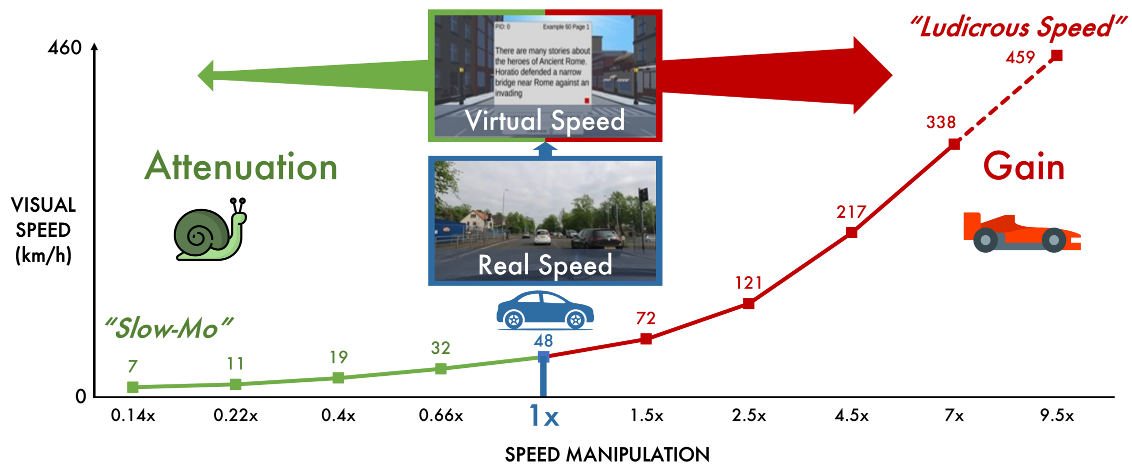

Figure 1: Vehicular Translational Gain and Attenuation are applied to the real motion of a car (~48km/h) to produce faster (up to 338km/h in Study 1, 459km/h in Study 2) or slower (down to 7km/h) visual motion in a VR city scene.

ABSTRACT

To prevent motion sickness, Virtual Reality (VR) experiences for vehicle passengers typically present "matched motion": real vehicle movements are replicated 1:1 by movements in VR. This significantly limits virtual applications. We provide foundations for in-car VR experiences that break this constraint by manipulating the passenger's visual perception of linear velocity through amplifying and reducing the virtual speed. In two on-the-road studies, we examined the application of *Vehicular Translational Gain (1.5-9.5x) and Attenuation (0.66-0.14x)* to real car speeds (~50km/h) across two VR tasks (reading and gaming), exploring journey perception, impact on motion sickness, travel experience and tasks. We found that vehicular gain/attenuation can be applied without significantly increasing motion sickness. Gain was more noticeable and affected perceived speed, distance, safety, relaxation and excitement, being well-suited to gaming, while attenuation was more suitable for productivity. Our work unlocks new ways that VR applications can enhance and alter the passenger experience through novel perceptual manipulations of vehicle velocity.

CCS CONCEPTS

• **Human-centered computing** → **Mixed / augmented reality**; • **Computing methodologies** → **Perception**; **Virtual reality**.

KEYWORDS

Perceptual Manipulation, Virtual Reality, Motion Sickness, Translational Gain, Automated Vehicles, Vehicular Gain, Vehicular Attenuation, Velocity, In-Car

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1 INTRODUCTION

Virtual Reality (VR) headsets offer passengers complete control over their visual and auditory perception of their journey - transporting them from their car, bus or train to any immersive virtual space. This has been shown to benefit and support a breadth of Non-Driving Related Tasks (NDRTs), from productivity [48, 54, 58, 62] to mindfulness [59] and gaming [3, 26, 75]. The use of VR headsets in moving vehicles can increase the likelihood of Motion Sickness (MS), which commonly arises as a result of sensory conflict between physical motion that is perceived by the vestibular system and what is perceived visually [65, 66]. However, immersive displays can also help prevent the onset of MS while supporting user activities. *Matched Motion* environments - scenes where the vehicle motion is conveyed 1:1 to the user in VR (e.g., [13, 26, 51, 53]) - can ensure that passengers have a consistent visual and auditory perception of their self-motion. This helps prevent any sensory conflict and so avoids significant MS [12, 13, 32, 38, 51, 62, 63]. Consequently, matched motion environments have become a fundamental component of consumer passenger VR experiences such as Holoride [3].

While matched motion environments in passenger VR may be necessary to prevent MS and ensure passenger comfort, they are also inherently limiting. For games, they constrain designers to experiences where the virtual environment must move in precisely the same way as the vehicle moves: a matched motion game played during a city drive (i.e., low speed, frequent turns) would feel quite different if played on a motorway (with high speed and few turns). For productivity applications, matched motion environments offer a virtual backdrop which does not necessarily contribute to, and indeed potentially visually distracts from, the primary task of reading, web browsing and more [19, 64], where faster background motion could potentially be less suitable, restricting when and where passengers can productively work on a journey.

For both in-vehicle productivity and gaming, it could be beneficial to manipulate the passenger's perceived vehicle speed in VR - for the former minimising visual distraction, and for the latter enhancing excitement and enjoyment. There is a long history of *perceptual manipulation* in VR [77], particularly the use of *translational gain* [29, 70, 71, 85, 87]: the manipulation of the ratio of real-to-perceived self-motion. A VR user walking 1m in reality might perceive 0.5m or 5m of movement in virtuality thanks to translational gain, supporting the exploration of larger virtual spaces from constrained physical ones. Research has found that lower levels of gain often go unnoticed by users [70, 71] and may not provoke MS symptoms [69, 74]. Engaging in other tasks also increases the likelihood of these manipulations going unnoticed [27]. Higher gains facilitate much larger virtual spaces and can often be used without negative effects on spatial orientation [70, 71, 87], but are mainly suitable for individuals who are more resistant to MS [74].

Translational gain has yet to be applied to real vehicle movement in VR. Doing so could result in a stronger sensation of MS due to the increased discrepancy between visually and physically perceived self-motion. Visual and vestibular self-motion cues are integrated based on reliability judgements and weightings, with information being processed as coming from one source even if it does not match completely [9, 10]. However, it is not yet fully known to what extent visual and vestibular self-motion presentation can result in discrepancy, so how much gain/attenuation can be applied to the visual motion, while still being processed as representing the same source as the physical motion, while minimising effects on MS [9, 20, 35, 80]. Moreover, translational gain in VR is generally applied to active movements, such as walking or grabbing [29, 70, 71, 85, 87], with its effects on passive self-motion yet to be explored. Passive self-motion as experienced in a vehicle comes with a dominance of visual motion cues over vestibular ones[10]. This suggests that: 1) we should be able to manipulate the visual speed to a larger extent (higher gain/attenuation levels) without the user noticing compared to the active movements explored in prior research, and 2) should allow us to apply higher levels of gain/attenuation without causing MS compared to active motion. The adaptive nature of the reliability weightings [11, 73] can be taken into account when applying the speed manipulations to make them either more or less noticeable.

This paper explores *Vehicular Translational Gain and Attenuation*, the manipulation of the passenger's perception of the real vehicle speed (linear acceleration) using VR. Varying the visual motion speed in relation to the physical speed of the vehicle could be used to alter the perception of journeys - making them feel faster, slower, longer or shorter. This greatly expands the available design space for developers and researchers to create a range of novel experiences, giving a whole new design dimension to manipulate for in-vehicle VR without provoking MS. For example, decreasing distraction or inducing relaxation in productivity applications through *attenuation* (gain of less than 1), or increasing excitement in immersive gaming through *gain* (values greater than 1).

We examined the effects of translational gain and attenuation applied to visual background speed across two studies and two different use cases: productivity and gaming. We first performed a multi-session study (n=17, 3 sessions per participant) using a vehicle driven along a predefined route through everyday traffic, exposing participants to ecologically valid motion profiles. Participants performed a validated cognitively demanding VR reading task [61, 62] as a proxy for productivity scenarios. The experimental conditions were tested in separate sessions to avoid cumulative effects of MS. Using the PassengXR motion platform [53], we exposed participants to visual motion that was either matched (1:1), faster (Gain) or slower (Attenuation) than the physical motion of the car. We measured passenger MS symptoms, their perception of real and virtual speed, perceived time and distance travelled, as well as their perception of safety, excitement and relaxation. In a follow-up study (n=10), we tested an immersive gaming scenario based on a popular space station *trench run* environment, with players experiencing dynamic, varying changes in gain and attenuation to explore how manipulating perception of velocity could be used in practice.

1.1 Contributions

Our work provides the following contributions to the fields of VR, motion sickness and vehicular experiences:

(1) Examines the impact of translational gain and attenuation applied to linear vehicular motion on productivity and immersive gaming in real-world driving;
(2) Evaluates the effects of these manipulations on motion sickness, demonstrating that high levels of attenuation are more

sickness-inducing than gain, but that levels of both can be applied without severely increasing symptoms;

(3) Provides novel insight into how linear speed manipulations can be used to improve or adapt the travel experience for passengers (safety, excitement, relaxation) and the perception of the car journey (duration, length, speed) without causing adverse symptoms;
(4) Demonstrates, for the first time, how linear speed manipulations suit different use cases: 1:1 motion and attenuation are better for productivity, with gain better for gaming.

2 RELATED WORK

2.1 The Role of VR in Future Travel and Motion Sickness

Humans spend a significant portion of their lives in transit. Commuting time has been steadily increasing over the last decades [18], with passengers filling this time with non-driving related tasks (NDRT), like watching movies, playing games, reading books or engaging in productivity-related activities. The use of immersive devices in vehicles to support said NDRTs is an imminent everyday reality, as companies such as Meta and Apple are positioning their eXtended Reality headsets for entertainment and productivity use on transport [4, 6] and with commercial platforms such as Holoride [3] already being available to consumers. The introduction of VR into travel allows us to overcome both restrictions of limited display space as well as uncomfortable content positioning [55]. VR will enable passengers to engage in immersive games and movies [53, 76] and work via displays of any size and number placed in ergonomic and non-nauseogenic positions [14, 41, 42, 48, 50, 52, 54]. Whilst research has commonly used motion simulators (e.g. rotating chairs [14, 62]) to examine the impact of simulated vehicle motion on passengers, the gold standard in terms of ecological validity remains in-car studies under real vehicle motion.

Around a third of passengers suffer from significant MS [37] with up to half of all car users reporting having experienced MS at some point in the last five years [68], with symptoms ranging from headaches to dizziness, nausea and even vomiting. The primary cause for these adverse symptoms is believed to be the mismatch between self-motion information being perceived from the the visual and vestibular systems [65, 66]. Vehicle passengers receive information about their movements from the vestibular system but often lack the matching visual input, particularly when engaged in NDRTs [15, 17]. One major drawback of using VR in transport is its potential to increase this experience of MS [37]. However, whilst VR can contribute to the experience of MS, it also provides a potential solution to resolving this sensory conflict, as it gives us complete control over the visual and auditory perception of the motion of the passenger.

2.2 Visual Motion Cues in Vehicular VR: Preventing Motion Sickness, but Constraining Experience Design

Several researchers have instrumented vehicles with motion sensors to detect and convey their movements to a VR user [26, 53, 88], typically via Inertial Measurement Units (IMU) for vehicle orientation and On-Board Diagnostic (OBD) readings for velocity. The result is that VR experiences can produce a visual sensation of self-motion that is congruent with physically perceived self-motion, reducing the conflict between the sensory systems and consequently reducing MS symptoms. This mitigation technique has shown strong potential in reducing the MS of passengers that engage in NDRTs [12, 13, 32, 38, 51, 62]. Visual motion can be integrated in various different ways into the virtual environment. It can be presented in the background, independent of the primary task a user is performing [51, 62]; it can be directly integrated into the virtual locomotion of the user, such as controlling the speed and direction of a virtual vehicle as it moves through the virtual world [26, 59, 88]; or it can be integrated in a more implicit way by subtly manipulating the position of a 2D display in the virtual space [22, 64]. Outside of the real car and VR context, research has also found that using peripheral visual displays - such as LEDs moving backwards along the left and right A-pillars of a static driving simulator to enhance vection - can modestly increase the perceived speed of the virtual vehicle by up to 20%, especially when displays are brighter or more LED groups are illuminated. This suggests that additional visual self-motion cues that elicit vection have the potential to manipulate one's journey experience [57, 78].

However, to-date vehicular VR researchers have predominantly employed visual motion displays that are *matched* 1:1 to the vehicle's real-world motion. This has the benefit of reducing MS, but it also inherently limits the nature of the VR experiences that can be presented - whether the user is working in a virtual workspace, or flying through space, the perception of motion will be inevitably the same.

Instead, we posit that the perceived speed of virtual motion could potentially be used to influence the emotional response or support the attentional demands of passengers engaging in NDRTs, or enable the virtual experience to traverse larger (or smaller) perceived distances than the physical distance. Playing a game where your spaceship appears to travel at 320km/h may be more exciting than the 50km/h of urban roads. Or when travelling at high speed down a highway, perceiving a slower speed may feel more calming, especially when viewing content that may be incongruent with high speed, such as a nature documentary. Such amplifications have already been shown to provide benefits for stationary or walking VR users, the topic to which we now turn.

2.3 Amplified Movement in VR

Translational gain is being used in VR to overcome physical space constraints, by accelerating or amplifying the mapping of physical body/arm movement to virtual movement, allowing users to walk faster or reach further into larger virtual worlds while being in a small physical space [28, 29, 70, 71, 85, 87]. Walking 1m in physical space can result in the user seeing 2m (2x gain), 10m (10x) or even up to 50m (50x) of movement in the virtual environment [28], though the gain is generally applied only to horizontal movement (x- and z-axes), as amplifying vertical movement (y-axis) could result in increased MS symptoms [28]. Users are not always able to detect gain applied to their self-motion, with research suggesting that gains of up to 1.6x-1.75x often go unnoticed [70, 71, 85], suggesting that the speed of travel or the physical space can be increased by up to 60-75% without the manipulation being perceivable. Gains of 2x may become noticeable but are often not experienced as problematic or sickness inducing [29, 69–71, 74, 85]. Even extreme gains (x50) can be applied to user motion without spatial orientation being negatively affected [70, 71, 87]. Research has suggested that gain levels of up to 1.5-2.0x are unproblematic and cause minimal MS, while higher levels significantly increasing symptoms [69, 74, 85]. This is in line with the sensory conflict theory as higher values of translational gain create a larger discrepancy between the user's physical movements and what they see. Individuals that were MS-resistant or only experienced extremely low MS [74] were not negatively affected by 10x gain, suggesting that some individuals can make use of extreme levels of gain. Active engagement in a task can also reduce the salience of the mismatch between the physical and visual movements, suggesting that even higher levels of gain/attenuation could be applied when passengers are using engaging applications [27].

No translational gain study in VR has applied manipulations to the passive self-motion experienced in a moving vehicle, nor investigated the effects of attenuation on MS, thus reducing the virtual movement relative to physical motion. Introducing a mismatch between the visual and physical motion increases the risk of MS and so it is necessary to understand what levels of discrepancy can be tolerated without increasing illness, as well as what levels of increased or decreased speed are noticeable or realistic.

2.4 Detecting Discrepancy between Visual and Physical Motion Cues

When moving through the world we rely on input from our visual and physical sensory systems to provide us with information about our own speed, the distance we have travelled and our orientation (heading direction). We typically perform two types of self-motion: active self-motion, such as walking or cycling (vestibular + proprioceptive system) and passive self-motion such as riding in a vehicle (vestibular system). When performing these motions we rely on dynamic visual information as well as physical information (proprioceptive and vestibular) to make estimates about the distance travelled, the speed and our orientation. The integration of such cues when they are perceived simultaneously is not yet well understood, but is believed to depend on reliability weightings of the information coming from the different sensory systems [9, 10].

It is believed that the vestibular system is optimised for the processing of *changes* in velocity (acceleration and deceleration) and higher derivatives (e.g. jerk movements), while the visual system is specialised to process velocity itself and changes in position [23]. Vision is also believed to be more sensitive to slow self-motion, with the vestibular system more sensitive to fast motion [7, 89]. When estimating the distance travelled during active self-motion (walking), participants relied more on physical (vestibular and proprioceptive) cues, while for passive self-motion they relied more on visual cues [10], in line with other work that suggests visual cues are weighted higher and more relied upon during steering tasks [83]. In contrast, Harris *et al.* [23] found that participants relied more on vestibular motion cues during passive self-motion.

Based on this, the distance and speed estimates in vehicular VR will be highly affected by the visual speed presented and by the gain and attenuation levels applied, with participants expected to rely more on the visual compared to the physically perceived self-motion. The reliability of visual input can be maintained for high levels of gain/attenuation if the levels slowly increase. This is due to the adaptive nature of the weighting of visual and bodily motion cues [11, 73]. This should also help reduce MS caused by any perceived sensory conflict. For multiple sensory cues to be integrated as coming from the same source (self-motion), they have to be presented in a close spatial and temporal fashion[9, 20, 35, 80]. A slow increase of gain and attenuation should benefit this cue integration and should promote the perception of both cues coming from the same source.

3 STUDY 1: GAIN AND ATTENUATION DURING A VR READING TASK

In this study, we examined the effects of gain and attenuation applied to the speed of visual background motion through a virtual city in VR in relation to real car motion, with a focus on experienced MS, perceived ride experience and reading performance. The research questions were: Does the usage and/or increase of gain or attenuation applied to the visually perceived self-motion affect...

- (**RQ1**) ...motion sickness symptoms (measured in real-time and *post hoc*)?
- (**RQ2**) ...the perception of the journey (travelled distance, time spent travelling, real car speed, virtual car speed)?
- (**RQ3**) ...the ride experience (safety, excitement, relaxation, realism)?
- (**RQ4**) ...task performance (reading speed, workload)?

3.1 Study Design and Setup

The study used a within-subjects design with MS level, ride experience ratings and task performance as dependent variables and *Motion Manipulation* (Matched Motion, Gain, Attenuation applied to the visual motion stimulus) and *Section* as independent variables. The experiment consisted of three motion manipulation conditions in which participants were seated in the rear seat of a car wearing a Pico 3 VR headset [1] being driven along the experimental route. Participants performed a reading comprehension task as well as a secondary attention task (to ensure they were focused on the display at all times) during the drive [62]. In all conditions, the virtual background behind the reading task served as a visual motion stimulus and moved past the participant based on the real car's velocity and orientation. The car journey in each condition was made up of four Sections Figure 2. The motion conditions (see Figure 1) were as follows:

Matched Motion The velocity of the visual motion stimulus was kept constant in all Sections and matched 1:1 to the real car motion;

Gain The level of gain applied to the visual motion stimulus based on the real car velocity increased with each Section (Section 1: 1.5 x car speed, Section 2: 2.5, Section 3: 4.5, Section 4: 7). At the speed of the route (speed limit: 30mph/48km/h) this translates to a max visual speed of 45mph (72km/h), 75mph (120km/h), 135mph (217km/h) and 210mph (338km/h, approximately the speed of a Formula 1 car) respectively;

Attenuation The level of attenuation applied to the visual motion stimulus based on the real car velocity increased with each section (Section 1: 0.66 x car speed, Section 2: 0.4, Section 3: 0.22, Section 4: 0.14). This translates to 20mph (32km/h), 12mph (19km/h), 6.6mph (10km/h) and 4.2mph (7km/h, approximately walking speed) respectively.

The conditions were presented in counterbalanced order to avoid ordering or learning effects and were presented in separate sessions that were at least 24 hours apart to avoid any cumulative effects of MS. The level of gain and attenuation was increased/decreased with each section to allow for adaption effects. We used an increasing gain/attenuation approach for several reasons. Firstly, to minimise motion sickness caused by the virtual speed manipulation as much as possible. The integration of visual and vestibular self-motion cues is adaptive in nature [11, 73]. Therefore, if the discrepancy between the two is slowly increased rather than jumping between extreme discrepancies (visual speed changes) the visually perceived self-motion is rated as more reliable and in line with the vestibular self-motion thereby reducing the perceived sensory conflict and therefore motion sickness. We hypothesized that higher gain/attenuation could cause more sickness, and so counter-balancing could deny some participants the chance to experience lower, tolerable gains, and would confound subsequent sickness measurements, meaning a gradual increase was more appropriate.

Secondly, ours is not a threshold study, but our approach is a practical way to investigate perceivable differences between real and virtually perceived self-motion in an in-the-wild in-car study, and the effect on task performance. Using a counterbalanced approach would accentuate differences between different gain levels, potentially making more modest gains feel comparatively slow (e.g. going from 7x to 1.5x). By utilising an increasing approach we aimed to identify at what point the changes became noticeable. Traditional threshold perception studies require a high number of short trials, which would not be feasible under varying driving conditions (e.g., variable car speed across trials), would require long periods of time in VR in the moving car, and such short trials would not allow us to adequately explore how speeds affect user experience or task performance. Finally, this approach also allowed us to include levels of gain well beyond only threshold levels, to identify the limits of what can be experienced in the car.

3.2 Driving Route

Participants were not informed about the driving route prior to participating in the study so they could make unbiased judgements about the journey (speed, distance, time). To ensure they did not get any information about the route participants kept the VR headset on throughout their entire time in the car. The experimental drive consisted of: 1) a five minute trip from the University to the start of the experimental route; 2) the experimental route (2.09 km); 3) two break points, one at either end of the experiment route, where the car pulled into a side street and stopped for participants to complete questionnaires and judge the preceding journey; 4) another five-minute trip back from the final break point to the University, see Figure 2. The four Sections of the experiment involved driving along the straight part of the route out and back four times.

3.2.1 Experimental Route. The route taken in this experiment can be seen in Figure 2. The route was made up of the experimental Section (shown in red in Figure 2), which was a 2.09km straight road with a 48kmh speed limit. The orange lines show the route taken to the break points between experimental Sections, and the green line is the route between the University and the experiment. The experimental route was chosen as it included 3 traffic lights per Section, with multiple instances of acceleration and deceleration. Driving along urban roads during everyday traffic results in high ecological validity. This, however, comes with a decrease in experimental control. The route was controlled for distance travelled , however, due to differences in traffic and red lights, the time each participant spent in the experiment varied. To control for traffic as much as possible, sessions were run during the late morning and early afternoon to avoid rush hour.

We chose a straight route for the experiment for several reasons. Rotational and linear motion are detected by different parts of the vestibular system, and previous research has explored the relationship between rotational movement and motion sickness in VR in isolation using rotating chairs [62] and a lot of research has already explored how rotational gain affects user experience and perception thresholds in seated/standing VR, e.g., [43, 67, 81, 84]. Linear motion is the most difficult to experimentally manipulate in VR, as it requires a lot of physical space to move the participant, and so it was valuable to be able to isolate the effects of linear motion as much as possible. Further, curved roads have more variable (and often lower) traffic speeds, whereas straight roads let us more frequently drive at maximum speeds of 50km/h (30mph). They also vary substantially in e.g. the degree of curvature, and this is exceedingly difficult to experimentally control without access to a test track. By focusing on linear motion only, our work is complementary to the breadth of work that has already examined rotational motion in isolation. Finally, This design is expected to affect motion sickness in passengers, as both curvy roads (lateral accelerations [25]) as well as straight roads (linear acceleration/deceleration) can cause strong motion sickness [25, 44, 79].

3.2.2 Virtual Environments. During the journey, participants were presented with two different virtual environments inside the headset. When being driven to the start of the experimental route, to the break points, and back to the University (see orange and green lines in Figure 2) participants were exposed to a simple virtual environment. They were seated in a virtual car being driven over a grass landscape with mountains in the far distance. They did not perform any tasks during this time. This virtual environment was presented to the participants during non-experimental sections of the journey to ensure they would receive visual information about their self-motion to minimise any MS induced during this time.

During the experimental sections of the journey (red line in Figure 2), participants were seated in the same virtual car but travelled along a straight five-lane city road with offices, houses, shops and a pavement on each side (using the Low Poly Megapolis asset pack [31]), see Figure 3 left. This scene was chosen as it represents a strong and familiar vection cue that is believed to elicit a strong sensation of self-motion [62]. The scale of the buildings, and width of the road, was set to match the scale and spacing along the real experimental route. The virtual car moved along the city road based

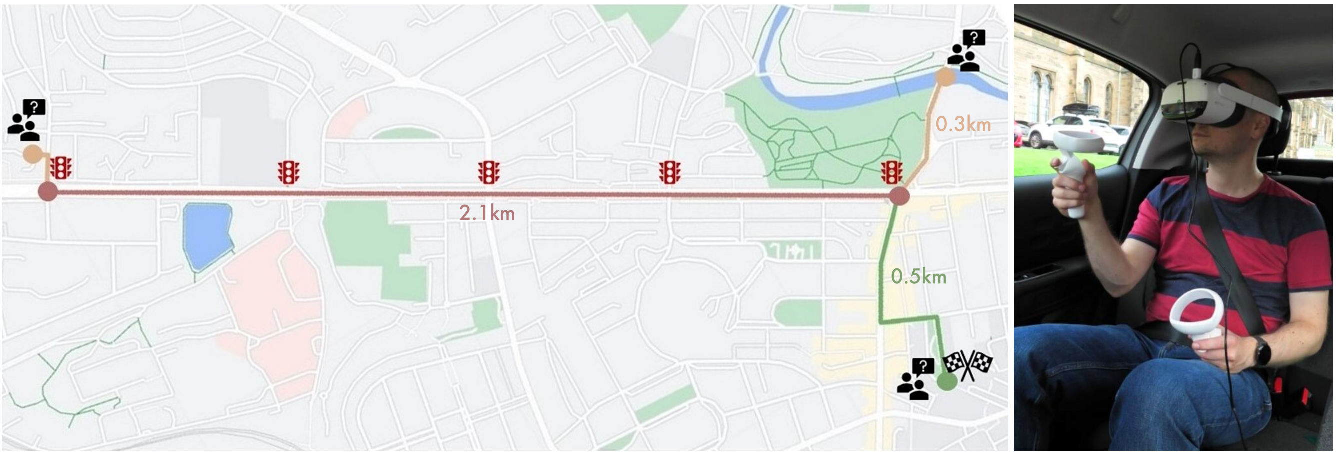


Figure 2: (Left) Route taken during Study 1. The red line shows the experimental route driven up and down for the 4 Sections of the study (including traffic lights). Orange lines show the drives to break points and the green line shows the drive to/from the start/end. (Right) Study setup in the car, with the Pico Neo 3 Pro Headset connected to the PassengXR motion platform [53] over USB.

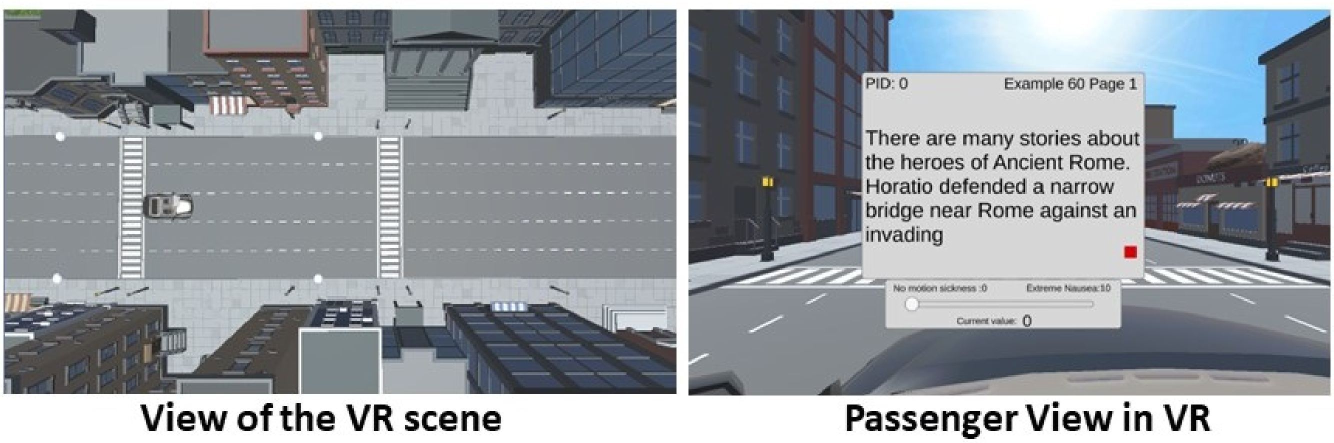


Figure 3: (Left) Top down view of the VR scene during the city-based reading task and (Right) Passenger view of the scene as shown in the VR headset.

on the velocity of the real car. The experimental route was straight without any turns, resulting in mainly linear forward motion, however, the virtual car moved laterally when the real car changed lanes (e.g. during filtering at junctions) and also rotated on all axes in accordance with the real car, such as pitch/tilt when going over speed bumps or road divots. The experiment used a motion platform (described in [53]) allowing for the head movements of the passenger in the virtual environment to be independent of the car rotations and for the orientation and velocity of the virtual car to be matched to the real one.

3.3 Productivity Task

People often perform productivity tasks when travelling, such as reading and writing emails or editing documents , and we based our experimental task on this. The task used the verbal reasoning section of the University Clinical Aptitude Test (UCAT) [2], which has previously been used in VR-MS research to represent productivity tasks [62]. This task tests reading comprehension. Participants used the VR controllers to control their reading speed of the passages that were presented in chunks of 20-30 words. After finishing one passage they were presented with multiple choice questions about the the content, see Figure 3 right. The purpose of this study was to convey visual motion, and so we chose to use a single virtual display - equivalent to a ~32-inch monitor at ~1m distance - that left peripheral vision unobstructed whilst still inducing cognitive load.

3.4 Measures

The following measures were used before, during and after each journey section as dependent variables:

Motion Sickness Participants filled in the Simulator Sickness Questionnaire (SSQ) [33] before each Section and after the last Section, which determined their overall experience of MS in each Section and condition. While immersed in the virtual environment and exposed to the physical motion, participants continuously rated their sickness level on the Misery Scale (MISC) [8]. A visual scale was placed underneath the reading task displaying their current level of MS and allowing them to change this continuously if needed (see Figure 3). To prevent participants from becoming too unwell the experiment was ended if they reached a score of 7, which represents *Fairly Nauseated* on the scale. The MISC scale and the meaning of its levels was explained to participants prior to the experiment;

Workload The NASA-TLX [24] workload assessment was administered at the end of each section to measure perceived workload;

Performance Task performance was determined by overall reading speed as well as the proportion of reading comprehension questions answered correctly. Reading Speed was based on the number of questions that a participant was able to read during each condition;

Ride Experience Participants rated their experience of safety, excitement and relaxation throughout the journey for each Section on a 11-point Likert scale, ranging from 0 not safe/exciting/relaxing at all to 10 extremely safe/exciting/relaxing. Additionally we used the REAL2 item from the Realism subscale of the IPQ Presence questionnaire to capture perceived consistency between real and virtual movement on a 7-point scale [86]: "*How much did your experience in the virtual environment seem consistent with your real world experience?*" from 0 (not consistent at all) to 6 (very consistent). We did not use the whole IPQ due to the number of other questionnaires, and because immersion was not a key focus for the study;

Perception of Journey Participants made judgements about the duration of journey, the distance travelled, the speed of real car and the speed of the virtual car for each section.

3.5 Participants

Twenty one participants took part in the study over a 8 week time window resulting in 55 session in total. They were recruited through an internal recruitment system and each participant was compensated £40. Participants with a strong history of MS (MSSQ scores over 30) were excluded from the experiment to ensure none of the participants were likely to suffer from extreme negative symptoms. Despite this precaution, four participants terminated the experiment early as they experienced high MS symptoms and felt unable to continue. This resulted in a final sample size of 17 participants, who ranged in age from 20 to 44 years (M = 26.24, SD = 6.78). Nine participants identified as male, seven as female, and one as non-binary. Gender had no effect on perceived MS in this study (using Kruskal-Wallis; Average MISC: $\chi^2(2) = 0.25$, p = .882; SSQ: $\chi^2(2) = 3.50$, p = .174). Seven participants had never used VR before, another seven had used it 1-10 times prior to the study, while the remaining 3 stated that they use VR on a regular basis (1 to 7 hours a week). Prior VR experience had no effect on perceived MS in this study (using a Kruskal-Wallis; Average MISC: $\chi^2(2) = 0.09$, p = .956; SSQ: $\chi^2(2) = 0.59$, p = .746). All experimental procedures were approved by the [anonymized for review] Ethics committee (approval number: 300210263), which gave clear guidelines on the driving procedures.

3.6 Procedure

The experiment consisted of 3 sessions one for each Motion Manipulation condition, with each session lasting around 60min depending on traffic. After a brief introduction and consent, participants were familiarised with the MISC scale and were given training on the VR setup and controls For each condition, participants first verbally answered the pre-condition SSQ. They were driven to the start point of the experimental route where the condition began. After each Section, participants were moved into the simple VR environment and verbally answered the post-section SSQ, the NASA-TLX, made judgements about their perception of the journey, feeling of presence and ride experience at one of the break points. This procedure was repeated 4 times driving the experimental route up and down twice. After finishing the 4th Section, participants were taken back to the starting point and were asked to judge whether the speeds they experienced in VR felt realistic in the given speed manipulation condition. After the experiment, participants took part in a semi-structured interview about their experience.

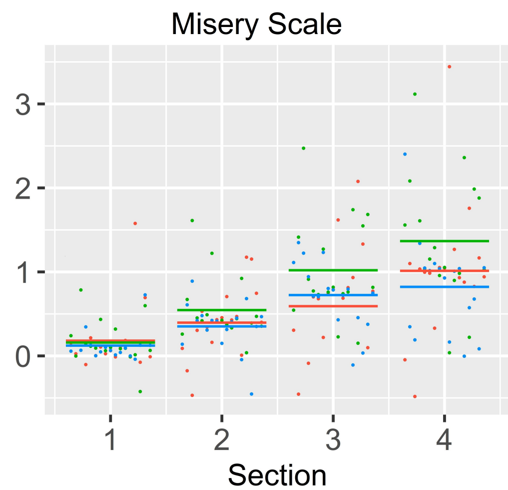
4 RESULTS

Results and statistical analyses can be found in Table 1.

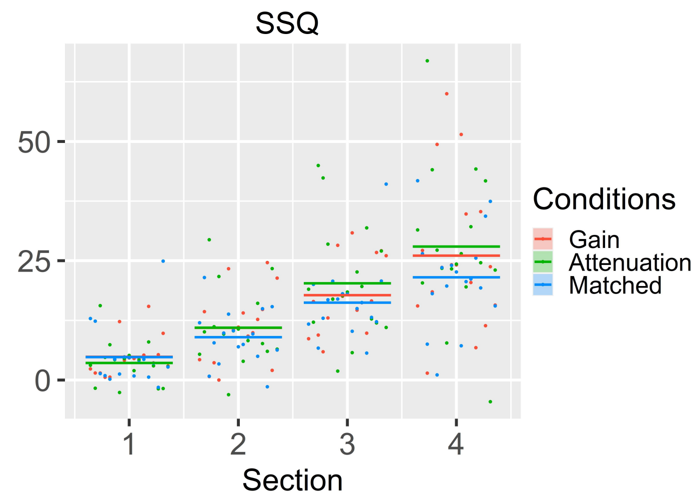
4.1 Motion Sickness - RQ1

A linear mixed effect model was used to analyse the data, including Condition, Section and their interaction as fixed effects, participant as random intercept and Section and Section duration as as random slopes. This model takes individual participant differences in the effect of the two fixed effects (predictors) into account as well as individual difference in the effects of Section and the duration of each Section. Linear mixed effect models, in comparison to more traditional ANOVAs, have advantages in their ability to model non-linear individual characteristics and deal with missing data, while allowing for multiple observations from the same observer [36]. Based on Lorah [45], we calculated Cohen's f2 for significant fixed effects. The model assumptions were checked for all of the following models by inspecting the residual plots revealing linearity as well as homoskedasticity. Pairwise *Post hoc* comparisons were performed for significant main effects utilising the Tukey method. Three participants did not experience any MS throughout the sessions according to their ratings on the Misery Scale, while two participants scored their overall experience of sickness as 0 on the SSQ. However, only one of those participants rated their experience of MS as 0 on both scales. The analyses below include the data of all participants. The same results were found when excluding the three participants. Unless mentioned, the same model was used for all of the following analyses.

*Model = lmer (Motion Sickness~ Condition *Section+ (1+Section+Duration Section|Participant))*



(a) MISC Score



(b) SSQ Score

Figure 4: Predicted Mean (a) MISC scores (0-10) and (b) SSQ scores for the four Sections. In this, and all the graphs,red lines represent Gain, green Attenuation, and blue lines represent Matched Motion conditions.

4.1.1 Average Misery Scale Scores. Due to Sections being of different duration, the MS rating was averaged over time for each Section resulting in 4 ratings per condition. Participants experienced significantly more sickness in the *Attenuation* compared to the *Matched Motion* condition. The manipulation of visual speed affected MS but only when speed was reduced. MS also increased over time and with each Section, see Figure 4 a.

4.1.2 Simulator Sickness Questionnaire. Analyses of the three SSQ sub-scales (Nausea, Oculomotor, Disorientation) showed similar results to the overall SSQ, so, for brevity, we only report total SSQ score. Participants scored their overall sickness the same in the three Motion Manipulation conditions, suggesting that the manipulation of the visual speed did not affect overall MS. SSQ scores also increased with each section, i.e., they increased as the time spent in the headset increased, see Figure 4 b.

4.2 Perceived Workload and Performance - RQ4

4.2.1 NASA-TLX Total. Analyses of the sub-scales Mental Demand, Physical Demand and Temporal Demand showed similar results to the overall workload scores, so, for brevity, we only report results for total workload score. For the sub-scales Effort, Performance and Frustration no significant effects of condition or Section were found. For brevity these analyses are not included here. Participants experienced significantly higher workload in the *Gain* condition compared to *Attenuation*. Mental Demand also increased over time and with increased manipulation of the visual speed.

4.2.2 Reading Task Performance.

Responses To investigate performance on answering the reading comprehension questions, a binary logistic regression model was performed. If participants did not finish an example text in one Section they could finish it in the next, which is why the following analyses focuses on the effect of Motion Manipulation condition only. No significant difference in performance was found between the Motion Manipulation conditions, $\chi^2(4)$=4.61, p=.329. In all conditions, participants answered around half of the questions correctly (*Gain*: M=46.07% (±.021 SE); *Attenuation*: M=50.66% (±.019 SE); *Matched*: M=51.76% (±.013 SE)).

Reading Speed A Friedman's ANOVA was performed to calculate the effect. A significant difference in reading speed was found between the conditions, $\chi^2(2)$=12.5, p=.002, W = .37. Participants read significantly more passages in the *Matched Motion* condition (M =11.85, SD = 2.92) compared to the *Gain* (M = 9.70, SD = 3.47; W = 11, p = .003) and *Attenuation* conditions (M = 10.03, SD = 3.21; W = 19, p = .014), no difference in speed was found between the Gain and Attenuation condition.

4.3 Ride Experience - RQ3

4.3.1 IPQ Consistency (Real vs Virtual). Participants experienced the *Attenuation* condition as significantly less consistent with their real environment compared to the *Matched motion* condition. Section had a main effect on perceived consistency but *post hoc* tests revealed no significant differences between the four sections.

4.3.2 Safety. Participants rated the *Gain* condition significantly lower for safety compared to the *Attenuation* and *Matched motion* conditions. Section did not affect Safety ratings, see Figure 5 left.

4.3.3 Excitement. Participants rated the *Gain* condition significantly higher for Excitement compared to the *Attenuation* conditions. Section did not affect Excitement ratings, see Figure 5 middle.

4.3.4 Relaxation. Participants rated the *Gain* condition significantly lower for Relaxation compared to the *Attenuation* and *Matched Motion* conditions. Section did not affect Relaxation ratings, see Figure 5 right.

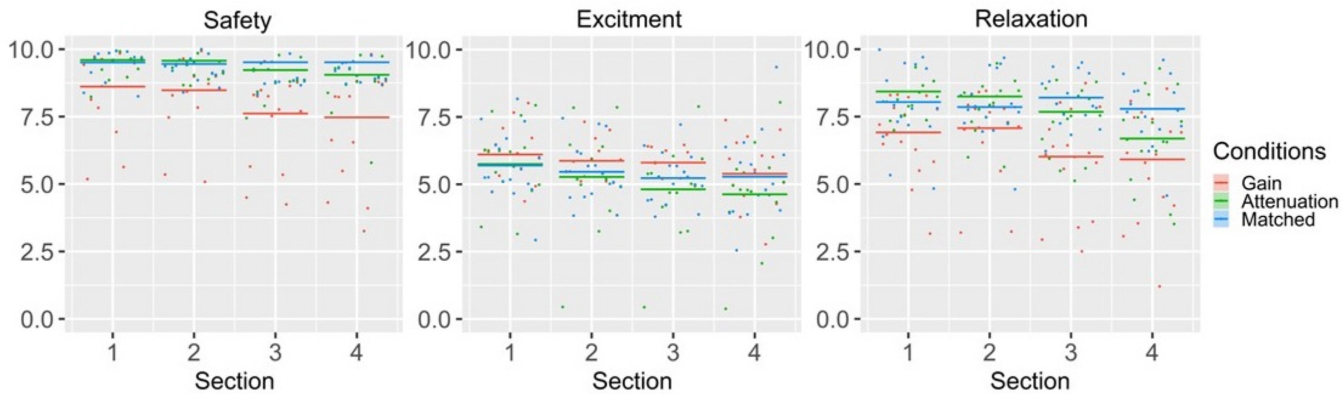


Figure 5: Predicted Mean (Left) Safety, (Middle) Excitement and (Right) Relaxation ratings for the four Sections.

4.4 Perception of Journey - RQ2

4.4.1 Journey Duration. We calculated the perceived time for each section taking the time judgement of the participant and subtracting the actual duration of each section. No significant effect of condition, section or their interaction on perceived journey duration was found.

4.4.2 Distance. Each section travelled was 2.09km (1.3 miles) long. Participants estimated the distance travelled to be significantly further in the *Gain* condition compared to the *Attenuation* and *Matched Motion* conditions. Section and their Interaction did not affect Distance judgements, see Figure 6 left.

4.4.3 Real Speed. Overall for all trials, the mean car velocity was 34.21km/h (3.59km/h), and the mean speed judgement was 40.72km/h (17.35km/h), giving a mean overestimation of 6.51km/h. The average non-zero speed of the real car (i.e. not considering zero velocity values when the car was stopped) did not differ between the Motion Manipulation condition or Section. This analysis was to ensure that the real car speed was the same for all condition and did not affect the judgements of participants. The route driven in this study was partly chosen as is allowed for various points of acceleration and deceleration as well as unbroken section at the maximum speed allowed on the road (48km/h). Participants spent 25.80% of the time the car was in motion at maximum speed (~48km/h) and almost half of the time (49.30%) at speeds over 40km/h (85%+ of max speed). Independent of the time spent at faster or slower speeds, the relative differences between real and virtual speed (i.e., the amplification factors) are constant.

The speed manipulation had a significant effect on the perceived real car speed in the *Gain* condition compared to the *Attenuation* and *Matched Motion* conditions, with participants perceiving the real car as going faster under Gain. Section had no significant effect on perceived speed but the interaction between condition and Section was significant. Therefore, we tested whether Section affected perceived real car speed for any of the individual conditions. Section had no effect in the *Attenuation* and *Matched Motion* conditions, however in the *Gain* condition the perceived real car speed increased with the level of gain applied to the virtual car speed. Suggesting that increases in gain resulted in participants perceiving the real car as going faster and faster while increases in attenuation had no effect on perceived real car speed, see Figure 6 middle.

4.4.4 Virtual Speed. We calculated the difference in perceived virtual and real car speed for each Section, taking the virtual speed judgement and subtracting the real car speed for each Section. Positive values suggest participants experienced higher virtual speed compared to the real car speed and negative values suggest participants perceived the real car speed to be higher than the virtual car. This analysis was done to test whether participants were able to detect the differences in virtual speed independent of the perceived real car speed.

Participants perceived the virtual car speed to be significantly higher in the *Gain* condition compared to the *Attenuation* and *Matched Motion* condition. Section had no significant effect on perceived speed but the interaction between condition and section was significant. Looking at the Condition separately, Section had no effect in the *Attenuation* and *Matched Motion* conditions, however in the *Gain* condition, the perceived real car speed increased with the level of gain applied to the virtual car, see Figure 6 right. Participants felt as though the virtual car was driving faster than the real car when higher levels of visual gain were applied.

4.5 Interviews

A single coder thematic analysis was performed identifying the themes from the post experiment interviews [30]. These themes were then discussed with, and confirmed by, a second coder.

4.5.1 Condition Preferences. The *Matched Motion* condition was the preferred condition by almost half of participants (8, 47.05%), while the *Gain* condition was preferred by over a third (6, 35.29%), with only 3 preferring *Attenuation* (17.65%). The Gain condition was, however, also found as the least preferred by almost half of the participants (7, 41.17%). Participants that preferred the *Gain* condition mentioned that the faster speed was fun and enjoyable (P1, P5, P13) with one participant suggesting that the faster speed was "more relaxing as it felt more realistic being in a car" (P17). Participants that rated *Gain* as their least favourite condition commented that the visual motion was too fast (P6) and was distracting

Measure	Factor	Main Effect DoF	F	p	f^2	Mean (SD)	Significant Post Hoc Comparisons: Comparison	DoF	t	p	d
Misery Scale	Condition	2, 163.72	4.01	.019	.11	**G**: 0.65 (1.66), **A**: 0.85 (1.39), **M**: 0.54 (0.87)	**Attenuation - Matched**	129	2.53	.03	.18
	Section	3, 32.39	3.41	.029	.14	**S1**: 0.20 (0.46), **S2**: 0.51 (0.83), **S3**: 0.86 (1.13), **S4**: 1.15 (1.54)	**Section 4 - Section 1** **Section 4 - Section 2**	15.8 15.9	2.89 2.85	.047 .05	.84 .52
	Interaction	6, 161.07	0.90	.493							
SSQ	Condition	2, 157.20	1.34	.263		**G**: 14.74 (9.07), **A**: 15.62 (22.22), **M**: 12.60 (16.60)					
	Section	3, 34.14	6.55	.001	.27	**S1**: 4.47 (7.25), **S2**: 10.19 (12.41), **S3**: 17.75 (19.46), **S4**: 24.48 (26.42)	**Section 4 - Section 1** **Section 4 - Section 2** **Section 3 - Section 1**	16 16 15.9	4.08 3.83 3.53	.004 .007 .013	1.03 .69 .90
	Interaction	6, 142.61	0.48	.825							
NASA - TLX	Condition	2, 154.45	4.12	.018	.06	**G**: 41.49 (18.96), **A**: 37.44 (18.63), **M**: 37.59 (17.23)	**Gain - Attenuation**	128	2.53	.034	.022
	Section	3, 52.82	4.61	.006	.07	**S1**: 33.75 (17.02), **S2**: 36.09 (16.50), **S3**; 41.47 (18.69), **S4**: 44.06 (19.46)	**Section 4 - Section 1**	16	4.08	.004	.56
	Interaction	6, 154.40	0.36	.900							
IPQ REAL2	Condition	2, 158.68	5.16	.007	.10	**G**: 4.03 (1.29), **A**: 3.81 (1.34), **M**: 4.24 (1.36)	**Matched- Attenuation**	118	2.92	.012	.32
	Section	3,30.60	3.46	.028	.05	**S1**: 4.26 (1.32), **S2**: 4.24 (1.26), **S3**: 3.96 (1.22), **S4**: 3.65 (1.48)					
	Interaction	6, 159.25	1.46	.196							
Safety	Condition	2, 171.71	27.15	<.001	.19	**G**: 8.09 (2.52), **A**: 9.34 (1.31), **M**: 9.51 (0.84)	**Gain - Attenuation** **Gain - Matched**	128 128	5.81 6.34	<.001 <.001	.62 .76
	Section	3, 42.98	1.51	.226		**S1**: 9.25 (1.21), **S2**: 9.18 (1.57), **S3**: 8.80 (2.10), **S4**: 8.69 (2.20)					
	Interaction	6, 169.21	0.98	.440							
Excitement	Condition	2, 175.99	4.03	.020	.02	**G**: 5.75 (2.55), **A**: 5.07 (2.55), **M**: 5.37 (3.02)	**Gain - Attenuation**	126	2.66	.023	.27
	Section	3,92.25	2.67	.051		**S1**: 5.80 (2.87), **S2**: 5.49 (3.07), **S3**: 5.24 (3.04), **S4**: 5.06 (2.81)					
	Interaction	6, 175.99	0.29	.940							
Relaxation	Condition	2, 171.57	15.78	<.001	.11	**G**: 6.19 (3.18), **A**: 7.44 (3.18), **M**: 7.71 (2.23)	**Gain - Attenuation** **Gain - Matched**	126 127	4.19 4.91	<.001 <.001	.39 .55
	Section	3, 94.86	3.25	.025	.05	**S1**: 7.57 (2.37), **S2**: 7.39 (2.43), **S3**: 7.02 (2.82), **S4**: 6.47 (3.02)					
	Interaction	6, 166.66	1.13	.347							
Journey Duration (Time Difference)	Condition	2,143.93	0.25	.782		**G**: 2.34min (3.48), **A**: 2.62min (2.85), **M**: 2.54min (3.83)					
	Section	3,22.20	3.00	.052		**S1**: 2.01min (2.57), **S2**: 1.69min, (3.05), **S3**: 3.24min (3.89), **S4**: 3.07min (3.74)					
	Interaction	6, 143.93	0.31	.932							
Distance	Condition	2, 165.57	11.23	<.001	.04	**G**: 3.87km (2.91), **A**: 3.01km (2.67), **M**: 2.82km (2.32)	**Gain - Attenuation** **Gain - Matched**	128 128	3.24 4.34	.003 <.001	.31 .40
	Section	3, 73.20	1.09	.358		**S1**: 3.02km (2.26), **S2**: 3.10km (2.65), **S3**: 3.31km (2.89), **S4**: 3.49km (2.89)					
	Interaction	6, 164.16	0.38	.894							
Real Car Speed	Condition	2, 175.19	28.69	<.001	.18	**G**: 49.21kmh (21.55), **A**: 37.63kmh (14.40), **M**: 5.33kmh (11.31)	**Gain - Attenuation** **Gain - Matched**	126 126	5.68 6.57	<.001 <.001	.63 .81
	Section	3, 166.23	0.62	.602		**S1**: 39.22kmh (15.49), **S2**: 40.92kmh (17.84), **S3**: 40.67kmh (18.39), **S4**: 42.08kmh (17.94)					
	Interaction	6, 175.46	2.31	.036	.03						
Condition separately	Gain	3, 45.57	5.85	.002	.04	**S1**: 41.64kmh (17.63), **S2**: 48.82kmh (22.93), **S3**: 53.82kmh (22.71), **S4**: 52.56kmh (22.30)	**Section 4 - Section 1** **Section 3 - Section 1**	45.7 45.4	3.36 3.51	.008 .005	.54 .60
Virtual Car Speed (Speed Difference)	Condition	2, 176.32	30.04	<.001	.38	**G**: 13.16kmh (24.56), **A**: -10.15kmh (18.47), **M**: -4.18kmh (15.49)	**Gain - Attenuation** **Gain - Matched**	127 125	7.08 5.22	<.001 <.001	1.07 0.85
	Section	3, 184.44	1.51	.217		**S1**: -4.12kmh (11.84), **S2**: -1.33kmh (13.65kmh), **S3**: -0.50kmh (23.27), **S4**: 4.38kmh (32.85)					
	Interaction	6, 175.92	2.77	.013	.08						
Condition separately	Gain	3, 47.98	8.24	<.001	.16	**S1**: 1.95kmh (7.47), **S2**: 7.33kmh (15.87), **S3**: 18.39kmh (28.19), **S4**: 24.98kmh (2.80)	**Section 4 -Section 1** **Section 4 - Section 2** **Section 3 - Section 1**	47.8 47.6 47.8	4.38 3.27 2.89	<.001 .011 .028	.97 .69 .80

Table 1: Breakdown of statistical testing, Means and SDs by measure, including *post hoc* tests. Cells in green highlight rows with a significant main effect. G=Gain, M=Matched Motion, S=Section.

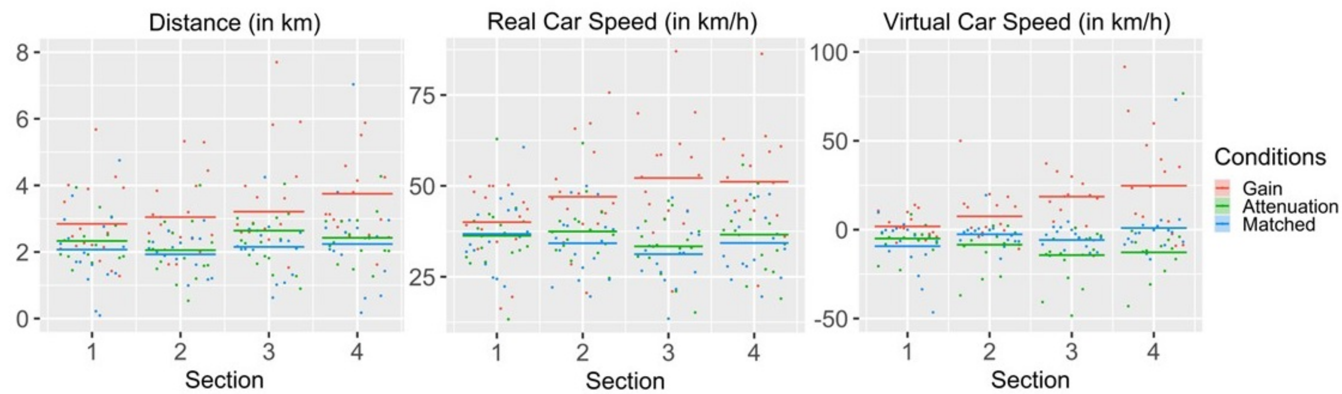


Figure 6: Predicted Mean (Left) Distance, (Middle) Real Car Speed and (Right) Virtual Car Speed for the four Sections.

from the reading task (P8). Participants that rated *Matched Motion* as their favourite condition commented on it being the most comfortable condition and the most realistic (P2, P7, P10, P14) and that it allowed them to concentrate on the task (P8). Participants that preferred *Attenuation* found it most relaxing (P9) and often did not consciously perceive a difference between Attenuation and Matched Motion conditions.

4.5.2 *Perception of Speed Manipulation and Effect on MS.*

Increase in Gain/Attenuation per Section:Two participants did not notice the speed manipulation in both the Gain or Attenuation conditions. One additional participant did not notice the manipulation in the Gain condition and five more did not notice the manipulation in the Attenuation condition. For most participants, the discrepancy in speed was noticeable in the last two sections where the manipulations were the highest. This suggests that the motion manipulation was less noticeable when the visual speed was reduced but more noticeable when increased.

P14: "Well, actually, until you said that I didn't know that the first [Attenuation] and third [Matched Motion] day was slightly different. It felt a lot similar to me"

Overall Speed Manipulation: When asked whether they noticed a difference between the three Motion Manipulation conditions, 11 did with 6 saying they did not (P9, P12 , P16, P18, P19, P20), with three of these participants stating that they believed that the real car speed was being manipulated and was different between the conditions, rather than the virtual car speed (P12, P19, P20).

P20: "I felt like we were almost on a highway"

4.5.3 *Attenuation Causes Discomfort.*

Even though the discrepancy between physical self-motion and visual self-motion was less obvious or consciously perceived by participants in the Attenuation condition, it caused the strongest MS symptoms (see 4.1.1).

P1: "It was the mismatch between what I felt and what I saw. Which was more disorienting in the slow condition. In the fast one it was just it was just fun, It was exciting. Whereas in the slow one - It was like - I could tell that my body is moving faster than my eyes think I am. And that distracted from the task."

4.5.4 *Attenuation and Matched More Suitable for Productivity.*

Participants suggested that the matched and slower speeds would be most suitable for productivity tasks, such as reading (P1, P3, P8, P13, P18) or taking meetings (P9). The slower matched speed was perceived as more relaxing (P6) and less distracting (P3), which can help productivity performance (P1).

P3: "I could definitely see being beneficial if I'm really focusing on something and I don't want to see them zipping by [houses in the background]. The increased speed (...) drew a lot more attention. "

4.5.5 *Gain more suitable for Entertainment and Fun.*

Participants stated that the gain condition was the most fun (P1, P3) and would be their preferred choice when playing a video game (P3, P5, P6, P7, P8, P16). They also suggested that the virtual speed could be matched to the pace of the game with faster paced games, such as an "adrenaline rush game, some racing game, or some arcade game" (P7) using faster background motion (P8) and slower pace games, such as "a crossword or Sudoku" (P8) being displayed with slower background motion. Some participants also suggested that a slower background could help balance out the fast pace of a game and make it easier to interact with it (P9, P19).

P3: "It was kind of fun when, you know, you can tell that the car is like driving through backstreets quite slowly and then you're, like, zipping around this kind of fantastic open space. So, there's definitely a fun aspect about it."

5 STUDY 2: GAIN AND ATTENUATION DURING A VR GAMING TASK

The participant interviews in Study 1 suggested that people would 1) like the chosen virtual speed (matched, faster, slower) to be part of, and relevant to, the experience, and 2) that the player experience in a video game could benefit from virtual speed changes. In particular, participants suggested that faster virtual speeds that match the pace of the game would enhance game enjoyment. Therefore, we decided to conduct a follow-up study (N=16) that adapted the city-based VR environment into a spaceship shooter game that dynamically altered the virtual speed based on an in-game narrative, and gathered players' subjective views on if/how the changes in speed enhanced or detracted from the game experience. This application directly integrates the visual motion and motion manipulation into the game experience and heavily focused on the effect of speed manipulation on the user experience and the game enjoyment using both semi-structured interviews as well as looking into presence, MS, game characteristics as well as journey experience measures.

5.1 Game Design

The game was based on a popular movie (about a war in the stars) sequence where spaceships fly along a three-sided "trench" on the surface of a space station and fire at enemy ships. Participants were told that they were the co-pilot in the mission and responsible for shooting enemy ships while their hyper-intelligent canine pilot R0-V3R controlled the speed of the ship and gave instructions (visible under a protective dome in front of the cockpit). The goal was to shoot as many enemy ships as possible and avoid taking damage from enemy fire. A laser cannon on the front of the ship was controlled by the right VR controller, and the trigger button fired a laser towards a green circular aiming reticle.

Points were earned for every ship that was destroyed. The amount depended on the size and the number of hits needed to destroy them, with points being subtracted every time an enemy ship hit the player. A defensive shield could be activated (for up to 6 seconds) to avoid damage and when enough points were collected a power-up was activated resulting in 10 seconds of rapid-fire of the players gun.

5.2 Study Design and Procedure

Study 2 followed a very similar procedure to Study 1, including the same roads and the same approach to the start of the route.It represents a more user experienced focused study compared to Study 1 and for brevity only included two Sections of the original route were used. Participants were exposed to two virtual environments during the study, both used a spaceship instead of a car. When being driven to the experimental route, and during break points, the spaceship flew through open space with movement mapped 1:1 on the real car, where different space stations and large ships were visible above a large planet. This scene was equivalent to the open grass in Study 1. Once the car arrived at the experiment route, the ship was 'warped' into the space station trench: a brief warp-speed visual effect (lines emanating from ahead of the ship) was shown before disappearing and revealing the ship now inside the "trench run" environment for the main game task.

In Study 1, one gain or attenuation level was used for the entirety of each Section, and speed changes were enacted while the car was stationary to avoid any comparative differences influencing participant perceptions. For Study 2, we changed speed both when stopped and while in-motion for two reasons: to explore how in-motion changes in speed affect MS and user experience, and to see how such dynamic changes could fit a game narrative. There was a total of nine speed changes (ten speeds in total) across the two experimental Sections: one change during the first Section and eight during the second. We also added an additional gain level of 9.5x (dubbed "Ludicrous Speed", after another famous space movie *Spaceballs*), as the fastest speed in Study 1 (7x) felt subjectively less fast in the context of the spaceship game. To minimise any potential MS caused by sudden and large changes in visual speed, the pilot R0-V3R would turn around and announce over the radio that the speed was changing and would give a reason as to why, such as "The engines are overheating, slowing down" or "The engines are fixed, speeding up" [39, 47].

Before starting the study, participants were given five minutes of practice with the game controls and mechanics. The car was then driven to the first Section, showing the open-space environment. This first section was split into two 0.96km long segments, starting with matched visual motion. Once the car stopped at a set of traffic lights halfway along the Section, the speed was changed to the "Ludicrous" speed (9.5x, 459km/h, 285mph). This was done to probe the experience of unexpectedly accelerating at greatly increased speed. After the first Section, the ship was warped out of the trench into space while the car stopped and participants answered questions. The ship was then warped back into the trench and, during the second Section (third segment), the speed of the virtual vehicle jumped multiple times while the car was in motion based on the game narrative, again at roughly equal driving distances (~0.23km/0.14 miles). Speed mappings alternated up and down between 9.5x -> 1.0x -> 4.5x -> 1.0x -> 7.0x -> 0.22x -> 4.5x -> 0.14x -> 9.5x Including both extreme *jumps* in speed and less extreme *jumps* in both directions (from slower to faster and from faster to slower). This was done to include a large variety of possible speed manipulation changes in the experience to later receive feedback on in the user interviews. We included fewer attenuated segments as it was found to be more sickness-inducing than matched motion and gain in Study 1.

5.3 Measures

After the first Section, and at the end of the study, participants completed the SSQ (simulator/motion sickness, rated 0-3, summed and weighted) [33], IPQ (presence, rated 1-7) [86] as well as the Immersion, Autonomy and Enjoyment sub-scales from the PXI (Player Experience Inventory, rated -3 to +3 and converted to 1-7 for analysis) [5]. We did not use the full validated version of the questionnaire, as sub-scales such as Meaning, Curiosity, Mastery, Progress, etc. were not relevant to our short self-contained game. Immersion and Enjoyment would indicate whether constant or changing speeds affected how immersive or fun the game was, and Autonomy would indicate if automatic speed changes reduced feelings of control. As in Study 1, participants also estimated how fast and how far the real car had travelled. Participants were also asked to rank the three segments to the game (the matched motion segment, the constant high gain segment and the speed *jumps* segment). Finally, a semi-structured interview was carried out investigating their game experience.

5.4 Participants

Sixteen participants took part in the study (10F, 6M) aged 21 to 43 ($M = 28.56$, $SD = 6.82$), none of whom took part in Study 1.

5.5 Results

5.5.1 Subjective Ratings. As SSQ, IPQ and PXI ratings were given between Sections, judgements were based on either the combined matched + "Ludicrous" speed experience (Section 1) or the combined

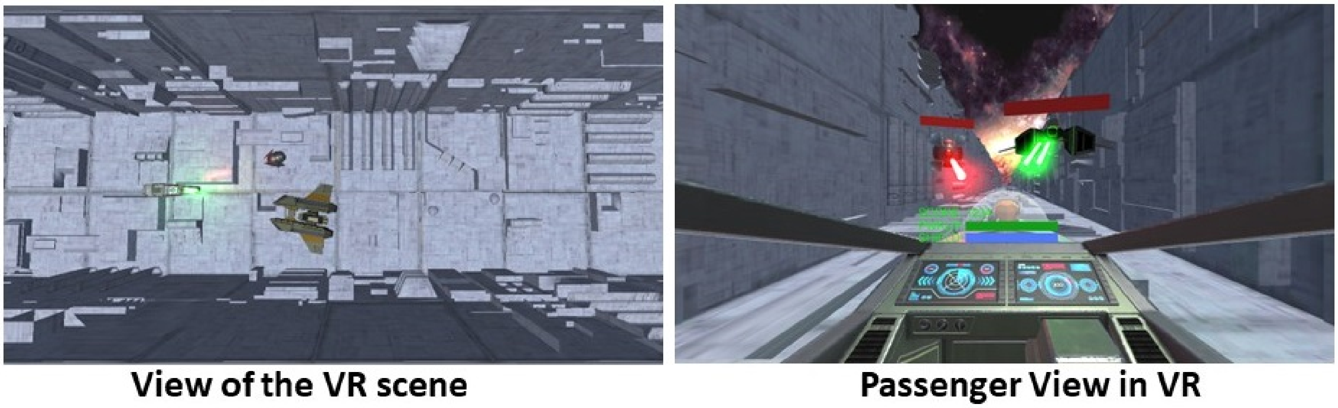


Figure 7: (Left) Top down view of the VR scene during the in-car VR game, and (Right) Passenger view inside the VR headset.

jumps/changes in speed (Section 2). The data were analysed via paired-samples t-tests.

There was no significant difference in the *MS (SSQ)* induced by the two sections (t(15)= 0.23, p = .822). The MS experienced was rather low overall for both Sections: Section 1 (M = 1.17, SD = 11.96) and Section 2 (M = 2.10, SD = 8.42). There were also no significant differences in *Presence* ratings between the two Sections (t(15)= 1, p = .333): Section 1 (4.38, SD = 1.36) and Section 2 (M = 4.56, SD = 1.09). Finally, there were no significant differences in the (PXI) sub-scales, with mean Immersion values of 5.98 (SD = 0.92) and 5.60 (0.93), (t(15)= 1.42, p = .178), mean Enjoyment values of 6.67 (0.61) and 6.50 (0.64), (t(15)= 1.46, p = .164), and mean Autonomy values of 4.92 (1.51) and 5.58 (1.58), (t(15)= 1.94, p = .072) for Sections 1 and 2, respectively.

For the subjective judgements of real car speed and travel distance, we asked participants to judge all three segments (Matched Motion, Ludicrous speed and the speed jumps) separately. Using repeated measures ANOVA, there were significant main effect of condition on *perceived car speed*, F(2) = 39.10, p <.001, η_p^2 = .723. Both the Ludicrous segment (mean = 70.22km/h, SD = 29,25; p < .001) and speed jumps (M = 50.16km/h, SD = 22.43; p = .008) led to significantly higher perceived speeds than during the matched motion segment (M = 43.62km/h, SD = 18.92). Ludicrous speed also led to significantly faster perceived speed than the speed jumps (p <.001) (see **??** in Appendix). There was no significant effect of condition on *perceived distance travelled*, F(2) = 2.54, p = .096. Speed jumps (M = 1.09km, SD = 1.02), Matched Motion (M = 2.31km, SD = 3.60km) and Ludicrous speed (M =3.71km, SD = 7.26).

5.5.2 Interview Responses. A single coder thematic analysis was performed identifying the themes discussed below [30], with themes being confirmed by a second coder.

High Gain Increases Enjoyment and Matches the Game Type. Participants were asked to judge which part of the game experience they preferred, and what they enjoyed: matched motion, maximum gain or the multiple speed jumps. Most people (n= 11) preferred the maximum gain segment of Section 1 and most people (n= 10) rated the jumps in Section 2 as their least favourite segment, with one person not noticing the jumps in Section 2. Participants described that they preferred the gain condition because the speed of the virtual space ship was still linked to the speed of the real car (unlike the jumps during Section 2). Whenever the real car accelerated or decelerated so would the spaceship, which made the experience more realistic. Technically the speed of the spaceship in the jump segment also followed the acceleration and deceleration of the real car with the jumps added throughout. The addition of the jumps could have resulted in participants not perceiving the real car motion as linked to the virtual motion. They also preferred the fast pace of this condition and suggested that it increased the overall game enjoyment.

P2:"it was fun to be in the moving car, like it was fun to feel the car stop and start with the space machine, that was fun."

Participant (P6) suggested that the faster virtual speed was mostly preferred over the matched motion as it fitted the game environment (spaceships) and such a fast speed would be expected in a game of this type, with another participant (P12) suggesting that the experience felt like "an extension of VR" similar to how 5D cinema experiences are an extension to traditional cinemas". 5D cinemas include 3D movies with seats movement and various special effects (Snow, Wind, Rain, Bubble, etc.). Participants described the gain condition as more "exhilarating" (P9, P13), more "exciting" (P14, P15), more "fun" (P4), "more immersive" (P4) and more "thrilling" (P8) compared to the matched motion condition. When comparing it to Section 2 with the multiple speed jumps, participants said that the mismatch between the visual speed changes in the game and the ones of the real car broke immersion, feeling "a bit weird" (P9) and "a little disjointed" (P10) and at times "less comfortable" (P14).

P4: "The faster one just felt more fun and then when it was changing back and forth I was kind of aware that it wasn't really matching what the car was doing too much. It kind of brought me out of it.

Attenuation, Large Speed Changes and MS. Participants responses suggested that the increase in speed during maximum gain did not affect their overall well-being, e.g., *P1:"And it's not as though that increase in speed made me feel any more sick at all".* However, two participants stated that the slower parts (which had attenuation values of 0.22x and 0.14x) in the jump conditions were quite uncomfortable and did not feel "good to play" (P1).

P1: "when the speed starts to vary it doesn't seem like it's based on how fast the car is moving anymore - it felt a bit disoriented when you've got the car you can feel it kind of moving a bit faster than the spaceship isn't moving at all, or is moving quite slowly. Parts where it picked up speed in those sections felt a bit better, but when it was moving slow [it was not good]. "

Having Control over Speed Changes. Seven of the participants stated that they would not want control over the virtual speed or changes in speed or were "not fussed" about having control. They stated that they would "rather have it [the speed of the virtual vehicle] matched with the car" (P4) and mentioned that for this type of game control over the speed is not important for game enjoyment (P11, P12). Three of the participants who stated they would like to be able to control the speed said that they would want to match the acceleration and deceleration to the real car movements and only increase the overall maximum speed.

P9: "So if I had control over it, I need to make it so that it was as fast as the car or faster than the car. But yeah, matching the stops and starts of the car"

Participants who would like control over the speed stated that this would make the game "more engaging" (P6) and "fun" (P2). One participant (P11) mentioned that it strongly depends on the type of game describing the game played as a "classical arcade game" which does not need to give the player control over speed or direction, while a more open game type could benefit from allowing the player to set minimum and maximum speeds prior to the game. The topic of allowing players to set certain speed parameters prior to the journey was brought up by another participant (P15) "For me, I'd liked to set it [speed] before I start the game because when I'm in game I want my attention just fully focused on that". Another participant (P14) mentioned that they would like to be able to increase the speed ones they have mastered the difficulty level of the game to make it more engaging and challenging.

6 DISCUSSION, IMPLICATIONS, AND GUIDELINES FOR DESIGN

This research demonstrates, for the first time, that linear *Vehicular Gain and Attenuation* can meaningfully alter the perception of vehicle velocity and consequent perception of the journey without unduly impacting motion sickness (MS). It offers an important new design parameter when presenting moving virtual environments tied to the car movement for passenger VR.

Study 1 found that vehicular gain was perceived as more noticeable compared to attenuation, with attenuation increasing experiences of MS (**RQ1**) as well as reducing the feeling of realism. Gain showed stronger effects on journey perception (perceived distance, real car speed (**RQ2**), ride experience (safety, excitement, relaxation (**RQ3**) as well as negative effects on workload and task performance (**RQ4**). Participant interviews highlighted a preference for background visual speed that was matched to or slower than the real car speed when engaged in a productivity-focused or relaxing task, and a preference of faster speeds when engaging in a game. This was emphasised by Study 2, where participants showed a preference for faster speeds as well as a single constant manipulation that still conveyed the relative accelerations/decelerations of the real car during a space-themed shooting game. Changing the speed manipulation mapping while the vehicle was in motion detracted from the game experience and the illusion that the real car was controlling the speed of the virtual spacecraft.

6.1 Vehicular Gain and Attenuation Are Not Equally Perceivable at City Driving Speeds

The speed manipulation was more noticeable to passengers when gain was applied to visual motion compared to attenuation. One potential cause could be based on the sensitivities for speed of the visual and vestibular systems. During self-motion, the visual system is generally more sensitive to slower speeds, while the vestibular system is more sensitive to faster ones [7, 89]. It could be that, in the Attenuation and Matched Motion conditions, the visual system was more heavily relied upon to perceive the speeds. In contrast, in the Gain condition the vestibular system would be relied upon more due to the high visual speed, but the vestibular system was not physically detecting equivalent faster speeds, making the manipulation more noticeable.

An alternative explanation could be based on vection research. Pure visual motion can induce a sensation of self-motion [16, 21], with faster visual motion eliciting vection sooner and eliciting a stronger and more robust sensation compared to slow visual motion [16, 34]. The fast visual motion in the Gain condition was therefore more likely to elicit a strong sensation of vection. This stronger sensation was likely perceived as more reliable than the vection induced by the slower visual stimulation, thereby being more noticeable to passengers. These are, however, only speculations based on limited related literature. A closer exploration into the detectability thresholds of Vehicular Gain and Attenuation is needed.

***Implication 1:* Vehicular Gain is more noticeable than attenuation (for speeds at or below 50km/h).**
In-car VR games portraying matched motion can be made more engaging, or other non-productivity experiences could be made more exciting, by adding gain to low-speed journeys.

6.2 The Effects of Gain and Attenuation on Motion Sickness

The MISC and SSQ results were not able to fully answer **RQ1**. Applying gain to the visual motion did not result in higher MISC or SSQ scores compared to the Matched Motion condition, and attenuation only resulted in higher MISC but not SSQ scores compared to the Matched Motion condition. This difference between the MISC and SSQ results could be due to them measuring slightly different aspects of MS. The MISC focuses mainly on Nausea related symptoms, while the SSQ includes a wider variety of symptoms. It could also be due to the symptoms overall being rather low with the SSQ not being sensitive enough to pick up such a nuanced difference between the conditions. The attenuation condition also resulted in lowest realism ratings which could be due to either the slow visual speed being perceived as unrealistic in the context of travelling along a city road or could be due to the stronger experience of motion sickness in this condition [82]. Our data also showed that MS symptoms increased over time with each Section, with the change in MS over time not differing between the Matched Motion and the two motion manipulation conditions. This would suggest that, rather than the increase in level of gain and attenuation applied to the visual motion, the *overall duration of exposure to the virtual environment and car journey* is responsible for this increase in MS. This would also suggest that the design of step-wise increasing the levels of gain and attenuation allowed participants to adapt to the discrepancy between the visual and vestibular motion input and was successful in minimising negative effects on MS.

> ***Implication 2:* Gain and attenuation can be applied to vehicular visual motion without inducing strong MS. The perception of a journey can be altered, and games can be made more engaging, without making the passenger feel unwell.**

> ***Implication 3:* Attenuation may not be noticeable, but may still negatively affect MS.** Attenuation should only be used for brief lengths of time unless paired with other MS mitigations.

One possible explanation for these findings could be the discrepancy between the expected and perceived visual motion during a car journey based on prior experience. The visual speeds displayed in the Attenuation condition were between 22.58km/h and 4.79km/h at the average speed of the car during the experiment (34.21 km/h). One would generally expect faster visual motion during a car journey. The finding that high levels of gain did not have the same negative effects could also be related to the visual system being more sensitive to the perception of slow self-motion, while the vestibular system is more sensitive to the perception of fast self-motion [7, 89]. This suggests there could be a different interplay between the two sensory systems for fast and slow self-motion cues.

> ***Guideline 1:* If an experience changes gain or attenuation level multiple times, it should do so gradually.** Our gradual increases in Gain/Attenuation in Study 1 did not increase sickness, but multiple large changes (such as in Study 2) may feel uncomfortable.

> ***Guideline 2:* Limiting the length of exposure to attenuated experiences is expected to be more important to maintain comfort compared to gain experiences** Exact time recommendations need to be investigated for each application.

6.3 Perception of the Journey

RQ2 proposed that applying gain or attenuation to the visual motion would affect passenger judgements of the car journey - in terms of estimating the duration, distance and real/virtual car speeds - as well as their experience of safety, excitement and relaxation. While applying attenuation did not seem to affect the journey experience compared to the Matched Motion condition, applying gain strongly affected estimates of distance travelled as well as virtual and real car speed. Participants believed that they travelled further in the real car when the virtual car was seen to be moving faster compared to the other conditions.

Participants also overestimated the real car speed when gain was applied, and this overestimation increased with increasing levels of gain. Similarly, participants perceived the virtual car as going faster than the real one in the Gain condition while, for the Matched Motion and Attenuation conditions, participants generally judged the virtual car speed slower than the real car speed. The overestimation of virtual car speed again increased with increasing levels of gain. Gain also had a stronger effect on ride experience compared to attenuation. Participants rated their experience of safety, excitement and relaxation similarly in the Attenuation and Matched Motion conditions, while the Gain condition was perceived as less safe and less relaxing than both other conditions, as well as more exciting than Attenuation.

For the visual motion cue to affect the perception of distance travelled and real car speed, we expected that it had to be weighted as reliable and as coming from the same source as the physical motion information [9, 10], which is generally believed to be more likely for smaller levels of gain and attenuation that go unnoticed. However, our findings suggest that for a speed manipulation to affect the perceived real car and virtual car speed, the discrepancy between the visual and physical motion had to be somewhat noticeable, as seen for the Gain condition.

> ***Implication 4:* Gain can be used to manipulate the journey experience.** The perceived distance travelled, the perceived speed of the real car, and the levels of excitement experienced can all be increased by applying Vehicular Gain.

> ***Guideline 3:* Increase the level of gain to make the real car speed feel faster.** This could make common journeys like commutes feel different, by varying the perceived speed or distance travelled.

> ***Guideline 4:* Use Attenuation or Matched Motion to preserve feelings of safety.** This may be useful for relaxation applications, or for those who are anxious about travelling, or who already have reservations or anxieties about being in autonomous vehicles [46, 56].

6.4 Matching the Manipulation to the Content

Some evidence for **RQ4** was found; faster visual speed was perceived as more mentally demanding compared to slower speeds. This could be due to the faster visual motion perceived in the background being more visually demanding and distracting [19, 64]. The speed of the visual backdrop had no effect on overall task performance, with participants answering the same proportion of multiple choice questions correctly in the three conditions. However, there was a strong effect of gain and attenuation on reading speed, with participants finishing fewer reading passages in these conditions. The higher levels of workload and visual distraction in the Gain condition could explain the slower reading speed[19, 64], while in the Attenuation condition, the higher levels of MS experienced by passengers could have had negative effects on reading speed [62].

> ***Implication 5:* Faster visual speeds cause higher reports of workload than slower ones.** This means that the use of Vehicular Gain could impact task performance.

Guideline 5: **Attenuation, and particularly Matched Motion, should be used when engaging in reading or similar productivity applications.** Amplified visual motion was generally not wanted during our productivity task and also caused higher workload than Attenuated motion, and reading speeds were significantly faster under Matched Motion.

6.5 Tying Changes in Virtual Speed to Changes in Real Speed

The passengers that took part in Study 2's shooting game generally preferred a constant 9.5x mapping of faster visual motion (with absolute speed varying with velocity changes of the real car) rather than changing the mapping between real and virtual speed while the car was in motion. They perceived the "Ludicrous speed" as more engaging and exhilarating compared to the Matched Motion and as more comfortable and immersive than the in-motion changes.

These findings give clear guidelines for the development of passenger VR games. Firstly, visual changes in velocity should be congruent with physical changes in velocity, independent of the overall visual speed or mapping. That means that when the car accelerates/decelerates, the virtual vehicle needs to accelerate/decelerate, and virtual speed should not increase/decrease unless the real car speed does too. Secondly, and related, if changes in the level of gain or attenuation *are* to be applied to the visual motion, this needs to be timed and congruent with changes in physical velocity. Ideally, this would occur when the real vehicle is stopped, thereby not resulting in a mismatch in perceived motion and not breaking immersion, and producing an exciting moment of unexpected acceleration. If this is not possible (e.g. on highways or when lights do not change), the gain levels can be increased during an acceleration, or attenuation during braking, thereby amplifying the physically perceived change in motion.

The consensus of participants was that the visual speed should be matched to the type of game being played to match with expectations. The speeds that one would expect from a space environment as presented in Study 2 would be rather high or even "ludicrous", while a different type of virtual environment, for example an underwater world, would potentially benefit from slower visual speeds.

Guideline 6: **Use higher levels of gain to enhance game enjoyment.** It will feel more exciting, enjoyable and better suited to the type of content.

Guideline 7: **Always slow down or speed up the visual speed when the real car is slowing down or speeding up** So that the visual speed never changes without a change in car speed.

Guideline 8: **Change the manipulation level when the vehicle is stopped, or coincide mapping increases/decreases with real accelerations/braking.** It will feel more comfortable and immersive.

6.6 Limitations

6.6.1 Experimental Route. The primary limitation of this research is that the driving route was a straight line with no turns and only occasional lateral motions (e.g. changing lanes). Therefore, the effects of Vehicular Gain and Attenuation on MS, ride experience and journey perception were only investigated for linear motion. Our findings, however, build the foundations and can guide future work applying translational gain and attenuation to more varied driving routes that will investigate how they can be applied to other aspects of vehicular motion, for example rotational gain applied to the degree of turn.

6.6.2 City Driving Speeds. The physical speed was limited to 30mph (48km/h), and averaged at 21.2mph (34.2km/h), so the effects of vehicular Gain and Attenuation might vary at different, and potential much faster speeds, for example on a motorway. For this experiment, we were limited to lower speeds for the safety of our participants, as required by our ethics committee. Attenuation could potentially be more noticeable at higher speeds, as the absolute change would be larger. The platform built for this study allows for this and for more complex routes involving turns, so further studies can investigate these issues.

6.6.3 Size of Productivity Workspace. We used a standardized cognitive task (UCAT) to represent productivity applications in Study 1, and it required only a single screen. However, modern productivity workspaces often include multiple physical or virtual displays encompassing much of the user's FOV. Adopting this setup in a car would block more of the visible peripheral motion, and would require additional head rotations and off-axis orientation, which would impact both user comfort (they would be more susceptible to motion sickness) and user experience (the speed manipulations would be less perceivable). We intentionally used only a single screen so that we could reliably explore the perception and impact of manipulated visual motion, but in order for multi-screen productivity to be suitable for in-car VR [49], alternative conveyances of motion may be necessary, such as altering the orientation of planar content [64].

6.7 Future Applications...

6.7.1 ...of Vehicular Attenuation. Whilst attenuation was not as effective as 1:1 matched motion with respect to MS, participants repeatedly reflected on its potential benefits for productivity, being suggested to be more relaxing, less distracting, and beneficial to focus and perceived safety. Consequently, attenuation could form a beneficial component of any productivity or well-being oriented passenger VR experience, being what we term a *minimally-invasive motion cue*, i.e. minimising distraction and maximising the passenger's capability to engage with the desired NDRT. However, to unlock the benefits of attenuation, future research needs to examine how we can overcome the potential MS penalty. We see significant opportunities to achieve this through leveraging complementary multimodal [63] or implicit [64] motion cues.

6.7.2 ...of Vehicular Gain. In contrast, gain has more obvious immediate uses. Our results repeatedly exemplified the benefits in creating more exciting gamified passenger experiences - pairing real motion with amplified visuals to transform mundane car movements into the exhilarating accelerations of a virtual spaceship. From formula racing to roller coasters, the use of gain could open the door to new games built on real vehicle motion that can be experientially different. And exciting games would no longer be limited to high-speed motorway or highway journeys, as low-speed city driving can be perceived similarly using gain. Regardless of the content type, research should explore how gain might affect the perception of longer, and potentially more boring, journeys such as cross-country travel. Our results suggest it could make these journeys feel shorter, which could reduce negative physical or emotional effects of road trips.

6.7.3 ...of Dynamically Applying Gain and Attenuation. The use of gain and attenuation could be dynamic and personalised. For example, when in a rush, the virtual speed might be increased (enhancing perception of "getting there" quickly) or decreased (calming the passenger's anxieties) depending on the individual's preferences.

6.7.4 ...of Manipulating Perception of Vehicle Motion across Extended/Mixed Reality. Our focus was on VR as it affords complete control over the user's perception of motion. But future passengers may also rely on mixed and augmented reality to support less immersive NDRTs and experiences, from gaming to productivity. Inspired by our findings, future work could consider manipulating motion perception across the mixed reality continuum. For example, depending on the capabilities of the Augmented Reality display being worn (e.g. additive versus subtractive displays [72]), such a headset may be able to render additional motion cues, such as moving 'starfields' (random-dot kinematograms) [60] rendered over reality as an overlay, or even virtual masks of the real vehicle windows to entirely replace the perception of the external environment.

6.7.5 ...of Applying Gain/Attenutation to Curved Roads. While we used a straight road, translational gain can and should also be applied to curved roads. The complexity of adding gain/attenuation with curves will depend on the use case and the chosen virtual environment (VE). Using GPS + map data, curves can be anticipated and the positions, scales, curvature etc of VEs and their contents can be adapted relative to current gain level and vehicle speed. Holoride's [3] SDK supports similar dynamic generation/placement of content based on road and map data, but only based on 1:1 car motion. In open VEs (e.g. outer space) curves can more trivially be incorporated.

6.7.6 ...of Manipulating Perception of Vehicle Motion on Motorways and Beyond. Finally, we only examined vehicular gain applied to low-speed city driving. But our findings could change significantly if we consider higher speeds, and other vehicles. Consider how the benefits and perceptions of gain or attenuation might change on the *Autobahn* (free to go >120km/h), or when applied to a VR-enabled real-world roller coaster[1]. Moreover, we only considered translational gain here, but *rotational gain* could further expand designers' capabilities to manipulate the perception of a journey by altering perceived passenger orientation changes whilst minimising sensory conflict. This could eventually enable a form of *redirected vehicular motion* for passenger VR, akin to how redirected walking [40] can manipulate perception of self-motion in roomscale VR. In this way, even relatively straight journeys on highways could be turned into meandering virtual journeys. We see our work as provoking a rich new series of explorations around the benefits of manipulating passenger's perceptions of vehicle motion. *"Light speed, too slow? We're gonna have to go right to ludicrous speed!"*[2].

7 CONCLUSIONS

In this paper, we investigated the effects of *Vehicular Gain and Attenuation* on motion sickness (MS), reading performance, ride experience and journey perception of car passengers, for the first time. Passengers using VR headsets sat in a real vehicle as it drove along a city road and viewed either a city or a space station scene where the speed of the virtual vehicle was controlled by the speed of the real vehicle, either matched 1:1 or with gain (1.5-9.5x) or attenuation (0.14x to 0.66x) applied. We investigated the usability of vehicular gain/attenuation across two broad contexts:productivity and immersive gaming, to demonstrate the generalisability of the manipulations.

Our results indicate that vehicular gain and attenuation can be applied to visual motion without causing significant MS, and gain can both change the perception of a journey (in terms of distance travelled, real car speed and excitement) and increase enjoyment of video game experiences. In contrast, attenuated and 1:1 matched speeds were more suitable for relaxing and productivity applications. Maintaining a constant level of gain or attenuation was more comfortable and led to better user experience than changing the mapping while the vehicle was in motion. Any changes in real speed should be conveyed by concomitant changes in virtual speed, and changes in mapping should best be done while the vehicle is stopped. Our work demonstrates the potential of using vehicular speed manipulations to avoid MS and improve the overall experience of passengers and opens up a new design space for VR applications in transit, both for productivity and immersive games. We discussed the implications for design and how our findings can guide the development of vehicular VR experiences. XR headsets will be an integral part of travel experiences in the future with the nature of VR allowing for a complete transformation of a passenger's journey experience transporting them into limitless virtual words. Our work moves the field forward by not only transporting the passenger into a different virtual space but also manipulating their experience of the real journey with the use of vehicular gain and attenuation.

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A APPENDIX