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UNIVERSITY OF CALIFORNIA
SANTA CRUZ

VECTION, PRESENCE, AND MOTION SICKNESS IN A VIRTUAL REALITY DRIVING SIMULATION

A dissertation submitted in partial satisfaction
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

PSYCHOLOGY

by

Benjamin Hughes

June 2023

The Dissertation of Benjamin Hughes is approved:

Professor Nicolas Davidenko, chair

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Vice Provost and Dean of Graduate Studies

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2023

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Abstract

Vection, Presence, and Motion Sickness in a Virtual Reality Driving Simulation

Benjamin Hughes

Over the past two decades, advancements in virtual reality have been researched and applied in numerous fields ranging from therapy to training to education. As the medium has evolved, so have the methods used for examining the subjective experiences and objective behaviors that take place while accessing virtual reality, including desirable factors like “presence” and “immersion” as well as undesirable experiences like motion sickness (more accurately, cybersickness). Within both research and recreational applications of VR, cybersickness represents an obstacle to the ideal user experience. The high prevalence of cybersickness in virtual reality applications limits users’ ability to enjoy and engage with the environment and hampers researchers’ ability to use virtual reality as an experimental tool. Virtual reality has the novel potential to create stimuli that generate unique responses in participants, such as the false perception of self-motion due to visual cues (an illusory phenomenon known as “vection”). Ameliorating the effects of cybersickness could open the doors for more fine-grained and generalizable research of such phenomena. Furthermore, a more holistic understanding of the illusory self-motion mechanism (vection) as it relates to sickness would help inform future studies on user experience within VR. This document summarizes a series of three experiments designed to investigate interactions between vection, motion sickness, and presence in the context of a virtual reality driving simulation.

Acknowledgments

To my parents, Paul and Marilyn, for their boundless love and support

To my friends, for their company and their loyalty

To my advisors, Leila and Nick, for their guidance and their patience

Chapter I – Introduction and Background

Vection and Self-motion Perception

The experience of perceiving self-motion while actually remaining static is known as “vection.” A common occurrence of vection involves looking out a train window and briefly believing your train to be moving forward, when in reality it was the adjacent train moving backwards. Vection is an important factor to research in both recreational and research applications of virtual reality. The experience of self-motion in situations where actual self-motion is impossible is very desirable for recreational VR (e.g. a VR rollercoaster, or a VR driving simulator). For academic applications, this allows researchers to learn more about the mechanisms by which self-motion is perceived. Vection has been defined in a number of ways over the years. Palmisano et al. (2015) provides a detailed review of the various definitions used throughout the literature. The most oft-cited definition is also the most specific and refers strictly to *visually-induced* illusions of self-motion. Other researchers have expanded the term to include illusions of self-motion that are induced by any of the other senses. Given the multisensory nature of virtual reality and its importance to the higher-order experience of vection, this paper shall adopt the latter definition. Note that this document does not recognize the definitions of vection which include real (i.e. non-illusory) experiences of self-motion.

In experimental settings, linear vection is typically induced using some form of display featuring an “optic flow” stimulus. These stimuli can vary in terms of their visual complexity, but generally feature a motion pattern expanding outward from a central point in the display (e.g. white dots expanding radially from the center of an otherwise black display). Radial, spiral, and oscillating optic flow presentations have been shown to result in vection (Kim & Khuu et al., 2014; Palmisano et al., 2016). Circular vection can also be induced by way of visual display. Many studies have employed an optokinetic drum (Bodenheimer et al. 2016) (a cylinder with stripes painted on the inside that is spun around a participant's visual field) to induce circular vection, while others have achieved similar results with large field-of-view digital displays (Mohler et al., 2005). Most presentations using optokinetic drums refer to yaw rotation, but some studies have also examined roll and pitch rotations (as well as combinations of axes) using digital displays (Bonato et al., 2009; Tanahashi et al., 2012).

Presence, Immersion, and Virtual Reality

Presence generally describes the degree to which a user (or users) feel(s) like they are in the virtual environment due to higher-order factors like interactivity and the physical realism of the scene (Heeter, 1992; Slater et al., 1994). Immersion, on the other hand, usually describes the degree to which the lower-order fidelity of the virtual environment influences one's experience by shutting out outside sensations (Slater & Wilbur, 1997; Slater, 1999). For example, a three-dimensional head-mounted display would be more *immersive* than a two-dimensional monitor because the former substitutes one's visual field more thoroughly. Similarly, an interactive game would induce stronger feelings of *presence* than a passively-watched movie. The key idea in differentiating these terms appears to be that immersion deals with relatively simple, explicit perceptions while presence speaks more to complex, implicit perceptions and interactions. Another meaningful distinction involves the fact that presence seems to involve more additive experiences (e.g., adding interaction, realistic scenes, and characters) whereas immersion seems revolve more around subtracting the non-virtual elements of the experience (e.g., using HMDs and headphones to eliminate/substitute outside visual/auditory cues).

Heeter (1992) established the earliest and most popular definition of presence, as the subjective sense of "being there." Furthermore, this definition emphasizes three main types of presence: subjective personal presence, social presence, and environmental presence. Slater (2009) posited that the necessary conditions for presence are the establishment of the "place illusion" and, to a lesser extent, the plausibility of the experience (Slater 2009). The "place illusion" (PI) is simply the illusion that one is present in the virtual/remote *place* and "plausibility" (PsI) in this context refers to the illusion that the virtual *actions* are taking place. Slater (2009) holds that establishing the place illusion requires physical realism within the virtual environment, whereas the establishment of plausibility merely requires the actions within the environment to be plausible to the user. These definitions help build a framework for analyzing the subjective experiences of users in VR, which will help ground behavioral research into presence.

Established Theories Concerning Motion Sickness

Motion sickness is a phenomenon primarily attributed to sensory conflict, although other theories provide alternative and supplemental explanations for the experience (Riccio & Stoffregen, 1991). In the context of virtual reality, motion sickness is often referred to as "cybersickness" and in some cases "simulator sickness." Visually-induced motion sickness (VIMS) also exists as a blanket term for sickness resulting from any dynamic visual display in the absence of real motion (Hettinger & Riccio, 1992). Just as with real-life motion sickness, a mismatch of sensory cues, particularly between visual and vestibular cues, is a plausible and well-discussed explanation for the phenomenon of both VIMS and cybersickness. Arcioni et al. (2019) draws a clear distinction between cybersickness and VIMS, in that cybersickness can result not only from visual stimuli, but also multisensory interactions (e.g., interactions between the participants' body movements and the visual cues provided in VR). For the purposes of this proposal, the terms "VIMS," "cybersickness," and "motion sickness" will be used interchangeably, given that all of the proposed experiments rely entirely on dynamic visual stimuli to induce vection.

Motion sickness tends to occur when the body is experiencing motion but does not have the appropriate sensory cues to process the experience. More specifically, motion sickness occurs when two sources of sensory information don't line up. For example, one perceives relatively stable visual cues while standing in the cabin of a boat at sea (as the cabin moves with them), but their vestibular signals are unpredictable and difficult to compensate for. This leads to a conflict that triggers the phenomenon of motion sickness. When one exits the cabin and receives congruent cues from their view of the horizon, the conflict is sometimes resolved. This explanation has come to be known as "sensory conflict theory," originating from observations by Claremont (1931) and formal definitions by Reason (1969) and Reason & Brand (1975). See Oman (1990) for a full review of the history and synthesis of sensory conflict theory, including its myriad revisions by medical and psychological researchers since its inception. This theory provides a helpful framework for evaluating instances of motion sickness in terms of their potential underlying mechanisms, as well as for evaluating instances of cybersickness that potentially arise from sensory mismatch.

Separate from sensory conflict theory, the “ecological theory of motion sickness” posits that motion sickness results from the body’s inability to correct its posture in response to movement (Riccio & Stoffregen, 1991). This theory (also occasionally labeled “postural instability theory”) attempts to ecologically address cases of motion sickness in which one is not experiencing any explicit sensory conflict, and also attempts to address cases in which sensory conflict is present but sickness is absent. Furthermore, this theory seeks to address the apparent individual differences in motion sickness susceptibility by implying that susceptibility is tied to the individual’s ability (or applied strategies) to maintain postural control, rather than an individual difference in one’s perception of sensory congruence. Maintaining postural control involves interactions between the sensorimotor systems. When the motor responses fail to achieve their goal in maintaining posture, the result is a sensorimotor conflict. The primary limitation of Riccio and Stoffregen’s theory is that motion sickness (as well as VIMS) has been observed and induced in many circumstances where posture was observed to be stable (and unrelated to varying levels of sickness), or where posture was fixed/restrained (e.g., in a chair, lying down, or on a chinrest) (McCauley et al. 1976; Warwick-Evans & Beaumont, 1995; Flanagan et al., 2004; Ji et al., 2009). In other words, if visually-induced sickness can happen even when the motor system is not engaged, then not all cases of motion sickness can be attributed to postural instability/sensorimotor conflict. That said, current research continues to investigate the potential value of postural stability as a predictor of cybersickness (Arcioni et al., 2019). It is entirely possible that both postural instability and sensory conflict contribute to motion sickness, albeit perhaps under different circumstances and with different roles. Furthermore, it is possible that postural instability plays a greater role in VR-induced sickness than in other visual/vestibular conflicts, due to the fact that participants cannot see their own legs/floor in most applications (and thus have more difficulty maintaining a stable posture). This notion is supported by the fact that standing VR experiences result in significantly more severe symptoms of sickness than their seated counterparts (Merhi et al., 2007).

The Potential Role of Presence in Vection and Motion Sickness

While there does not appear to be empirical research directly manipulating the effect of vection on presence, several studies have speculated on the relationship between the two variables. Given that vection requires a convincing visual stimulus to manifest, it is often assumed that the two variables are connected. Riecke et al. (2005) found that spatial presence and scene consistency showed strong positive correlations with vection “convincingness” ratings. Furthermore, they found that vection onset time correlated negatively with the same subscales (i.e. vection occurred faster when spatial presence was higher). In a meta-analytical review of presence and cybersickness research, Weech et al. (2019) noted that vection and presence are enhanced by many of the same factors, including the minimization of sensory conflict. In general, vection seems to take place when sensory conflict is minimized (e.g. vection-breaking vestibular cues are not present) and the user feels as if movement is plausible. This is further demonstrated by studies in which user-generated motion (e.g. using one's feet to "spin" the chair in a circular vection scenario) enhanced the experience of vection (Riecke, 2006). They also found that presence and cybersickness were negatively correlated in this scenario.

Given the similar circumstances under which vection, cybersickness, and presence occur, further investigation into their relationship is necessary. More specifically, the complex, seemingly paradoxical relationship between presence, vection, and motion sickness should be fully explored. If presence is positively correlated with vection but negatively correlated with sickness, it could potentially serve as a moderating factor between the two. Vection and cybersickness also share a complex relationship, with recent research demonstrating that subjective reports of vection strength correlated positively with cybersickness intensity (Teixeira, 2021).

It is possible that other factors, such as postural stability and postural affordances, could explain this relationship. For example, in situations where posture is secure (e.g. seated, back-supported, head-rested) and vestibular cues are minimized, presence could have a negative correlation with cybersickness, indicating a lack of sensory conflict. In situations where posture is insecure (e.g. standing, unrestricted movement), a strong sense of presence in the virtual environment could have a stronger conflict with the vestibular cues provided by the real environment, potentially resulting in greater sickness.

Sensory Re-weighting and Self-motion Estimations

The idea of "sensory re-weighting" (a phenomenon in which different sensory modalities shift priorities in response to changes in the environment/stimuli) could potentially explain this type of complex interaction (Gallagher, 2019; Gallagher et al., 2019). Harris et al. (2000) demonstrated that, in the case of simultaneous physical and visual self-motion cues, participants tended to rely more heavily on physical (vestibular) cues when estimating distance. They also found that, in the absence of physical cues, visual motion cues (optic flow presentations in a head-mounted display) were "perceptually equivalent to about half the physical motion." Several studies have demonstrated that participants' perceived sense of "uprightness" can alter the effect of self-motion illusions – specifically, one's orientation can alter one's prioritization of simultaneous visual and vestibular cues, which ultimately affect the degree to which one experiences visual reorientation illusions. Gallagher et al. (2019) demonstrated that VR-induced vection can modulate one's vestibular processing (as assessed by vestibular-evoked myogenic potentials). Furthermore, Ward et al. (2017) demonstrated that as participants are tilted along the roll axis, they tend to rely more heavily on visual cues than vestibular cues in estimating the subjective visual vertical (or "upright"). All of these results point towards a multisensory integration model in which the mind dynamically re-weights sensory inputs depending on which cues are more reliable at a given time. This dynamic re-weighting is further evidenced by Ernst, Banks, and Bülthoff (2000), in an experiment that showed that haptic feedback has a greater influence on one's perception of surface-slant in cases where visual cues are unreliable (e.g. in the absence of binocular disparity).

Potential Link Between Posture, Vection, and Motion Sickness

Posture interacts with the perception of both motion and orientation. Numerous studies have demonstrated that the perception of orientation is less accurate when the body (and therefore head) is recumbent (e.g. tilted 90 to 180 degrees) compared to when it is upright. (Witkin & Asch, 1948b). Furthermore, several studies have demonstrated that tilting of the head can strengthen visual tilt reorientation illusions, although it should be noted that these studies involved illusory tilt along the roll axis rather than the pitch axis (Witkin & Asch, 1948a; Young et al., 1975; Ward et al., 2017). This could potentially carry important implications for vection and other visually-induced illusions. For example, it is possible that errors in judgment of pitch-related orientation, acceleration, or velocity would also increase when the participant is tilted backwards along the pitch axis. It should also be noted that in most of these studies, the visual field was fully encompassed by the display of the stimulus, such that visual information about one's actual orientation was not available. Head-mounted VR displays provide a similar level of visual encompassment.

Given that posture/orientation can modulate one's visual perception, it holds that illusions relying on visual perception (e.g. vection, presence) would be affected by, for example, lying down. Within the postural instability theory in mind, two important questions regarding posture's effect arise. First, does posture have an effect on the believability of the virtual environment? Second, does posture have an effect on the prioritization of different sensory cues (e.g. visual over proprioceptive cues)? Given that posture could affect both believability *and* sensory cue prioritization, it is possible that different seating/head orientations could have a multi-layered interaction with both higher-order perceptual experiences like vection and presence, as well as lower-level phenomena such as motion sickness.

Presence and Cybersickness/Visually-induced Motion Sickness

Several studies have examined the potential link between presence and cybersickness, although the direction of this relationship is still unclear. Naturally, one would assume that the experience of cybersickness would lead to what Slater and Steed (2000) and Slater (2002) would call a "break in presence." Breaks in presence represent moments where the user ceases to behave as if they are in the virtual world due to some presence-interrupting event. In the context of immersive VR experiences, breaks in presence are considered undesirable (except in the context of research). Weech et al. (2019) provide a comprehensive review of papers that attempt to investigate presence-cybersickness connections. Although they found a preponderance of a negative correlation between the variables across some studies, several other papers found a non-significant or positive relationship between the two, thus indicating a potentially complex interaction. The review also acknowledges that this field of research suffers from small sample sizes and inconsistent methods of display. Weech et al. (2019) suggest that sensory congruence between visual and vestibular cues could contribute to both an increase in presence and a reduction in cybersickness, in ways that have not yet been explicitly manipulated or modeled. As noted earlier in the introduction, much of the research in this area took place before the advent of modern head-mounted displays, underscoring the need for modern experiments of this nature.

Current Experiments to Investigate the Relationship Between Vection, Motion Sickness, and Presence in a Virtual Driving Simulation

The current set of experiments utilize realistic VR scenarios to measure vection and motion sickness responses. Many two-dimensional vection studies present minimalist visual stimuli (e.g. white dots forming an optic flow pattern, or colored bars rotating around the viewer) to stationary observers with fixed viewpoints (e.g. chinrests, looking at a fixation point, etc). However, during typical VR gameplay, users experience VR-induced vection and motion sickness in more complex visual environments that allow them the freedom of head and eye movement. In order to better understand these phenomena within these contexts, the following experiments employ a realistic driving simulator (on a fixed virtual course) to consistently induce vection and examine its relationship to motion sickness and other perceptual and behavioral variables.

Driving simulation was chosen as the visual scenario for two reasons. The first being to attempt to solve the problem of sickness-inducing locomotion in virtual reality. The physical space in which virtual reality games and applications are played is limited, which means that those applications must employ various methods of moving around the virtual world. While there has been little empirical research on this topic, many game developers have already settled on several different modes of locomotion (e.g., point-and-click teleportation, sliding, climbing, and arm-swinging) which vary in terms of their sickness incidence. For driving games, the method of locomotion is simple and low-impact in terms of sickness, since the user has a relatively stationary visual frame of reference (the car) that does the moving for them. This method of locomotion is also relatively easy to control in an experimental setting, whereas other more freeform methods allow for more user control and variation. Second, driving simulation has speculative connections to the experience of real-life driving. Although the driving simulator in the current experiments did not employ vestibular cueing, the stereoscopic presentation of a realistic track in a realistic vehicle allows for greater ecological validity and immersion than a standard optic flow field. The current experiments presented the driving simulation using pre-recorded laps, so the user is not in control of the vehicle’s movement. This was chosen in order to maintain consistency between presentations of the visual stimuli, and also to make speculative connections to the experience of autonomous driving.

Experiment 1 serves as a preliminary study to determine whether posture has a direct influence on vection, motion sickness, and/or presence. Given that recumbent positions can make judgments of visual orientations less accurate, it stands to reason that this would contribute to one's sense of both presence and vection. When the accuracy of one's perception is reduced, illusions are generally strengthened. Both vection and the experience of presence are higher-order illusions that rely on ignoring or de-prioritizing the signals received by one or more senses (e.g., disregarding vestibular cues that would suggest stillness). The velocity of the visual stimulus will be manipulated to test the efficacy of the VR driving simulator as an accurate inducer of vection (e.g., vection should be higher at higher speeds). This experiment also involves two arbitrary starting positions on the virtual race track, to confirm that the phenomena of interest occur generally (rather than under specific visual circumstances). In the reclined portion of this experiment, the presentation angle of the visual stimulus is pitched 30 degrees upward to match the participant's viewing angle (e.g. the ground is parallel with the participant's eyeline).

Experiment 2 employs a similar design to Experiment 1. It features a baseline stationary condition for all lap conditions in order to make more accurate comparisons (e.g. sickness whilst still vs. sickness whilst "moving"). It also includes a reclined position with an unadjusted viewing angle (e.g. the ground is pitched 30 degrees downward relative to the participant's eyeline) in addition to the adjusted viewing angle used in Experiment 1. The unadjusted viewing angle includes less visual cues to self-motion (e.g. looking up at the trees vs. looking straight at the road). To control for this reduction in available visual cues, this experiment also includes a condition in which the participant is sitting upright but the visual scene is pitched downward to the same degree. By including these four conditions that fully dissociate posture and available visual self-motion cues, this experiment explores two potentially independent effects on vection, motion sickness, and presence. Additionally, this experiment manipulates the velocity of the laps in a more consistent manner than that of Experiment 1 (specifically, by taking a single lap and slowing it down to 50% speed, rather than driving two laps at different average speeds).

Experiment 3 manipulates the observer's facing direction relative to the perceived motion and tests the same dependent variables as the prior experiments. Specifically, this experiment compares radially expanding vection (e.g. regular forward-facing position in the car, as in previous experiments) with side-facing translational vection (e.g. left-to-right motion, as if looking out the side window of a moving vehicle) as well as radially contracting vection (e.g. backward-facing self-motion, as if driving in reverse while looking out the front window). All three types of optic flow cues have been shown to induce vection, but few studies have compared the strength of these types of vection-induction. This experiment does so in a realistic context.

Chapter II – Experiment 1: Effect of posture (upright or reclined) and speed on vection, sickness, and presence

This experiment investigated the effects of posture and speed on vection magnitude, sickness, and presence. The goal of this study was to examine whether a reclined posture would mitigate the effects of motion sickness by reducing the salience of vestibular cues and thus minimizing the sensory conflict between visual and vestibular inputs. Additionally, this experiment manipulated the speed at which the stimulus was presented, which should affect both vection magnitude and motion sickness severity.

Method

Participants

Of the 24 participants that were recruited for the study, 8 participants dropped out of the experiment early due to motion sickness were excluded from all analyses. The final dataset included 16 undergraduate students from the UCSC SONA subject pool (8 male, 8 female) between the ages of 18 and 21.

Design

This experiment employed a within-subjects, repeated measures design in which all participants completed all possible lap conditions in a randomized order within blocks (block order is also randomized). Trial order was counterbalanced across all subjects. Seating posture was manipulated across two blocks (upright/reclined) and stimulus speed (fast/slow) was manipulated across trials. This experiment consisted of eight trials across two blocks. Stimulus speed was randomized within each block.

Materials

Hardware

The virtual reality stimuli for this experiment was be presented on an HTC Vive head-mounted display. A computer tower with a GTX 970 Ti GPU and 16GB DDR3 RAM was used to run the associated software.

Software

The lap stimuli were presented through the "replay" feature of the popular consumer racing simulator *iRacing*. Several factors motivated the decision to use this program. The replay feature allows for consistent repeated presentations of a given lap or series of laps, such that each participant would experience the exact same driving (albeit in randomized/counterbalanced orders). Furthermore, iRacing is popular in the racing simulation gaming community due to its visual realism, faithful reproduction of real-life tracks/cars, and customizability. An OpenVR plugin was utilized to allow for VR support.

During the experiments, participants' head rotation data was collected using Brekel OpenVR Recorder. This software converts live-action movements of the headset along three axes (yaw, pitch, and roll) to a .csv file. These files can then be analyzed to determine the participants' head rotation velocity and deviation from center over the course of a given lap.

Figure 1. Screenshot from the iRacing stimulus.

Stimuli

The lap stimuli were recorded within iRacing. All laps took place within a virtual rendering of the Nurburgring Nordschleife race track. Laps started from one of two arbitrary starting positions and lasted 60 seconds each. Half of the laps were intentionally driven "slow" (at an average of 90mph) while the other half were driven "fast" (at an average of 120mph). Each lap (relative to the starting position) had the same number of turns. Realistic and time-synchronized engine sounds were present in all laps.

Procedure

Participants arrived, signed consent forms, then put on the head-mounted display with the help of a research assistant. They were then randomly assigned to a seating position (upright or reclined) which they maintained for the first four trials of the experiment. During the reclined portion of the experiment, the pitch angle of the virtual environment was adjusted 30 degrees upwards to account for the angle of the participant's head, such that the track was parallel with the user's eyeline. The first four trials consisted of laps around the track described in the "Stimuli" section. Each lap was either "slow" or "fast." Additionally, each lap started from one of two arbitrary starting positions (Positions A and B). The order of these laps (fast/slow, A/B) was counterbalanced within each block. After each lap, the participant was asked to self-report the three variables of interest: vection magnitude, motion sickness, and presence, on a scale of 1-20. The participant was then asked to remove the headset and complete a midpoint survey assessing overall motion sickness among other variables. Then the participant changed to the alternate seating position and completed the second block of trials. Following the second block, participants completed a demographic survey.

Results

The following analyses utilized a three-way ANOVA that included gender as a between-subjects factor.

Vection Magnitude

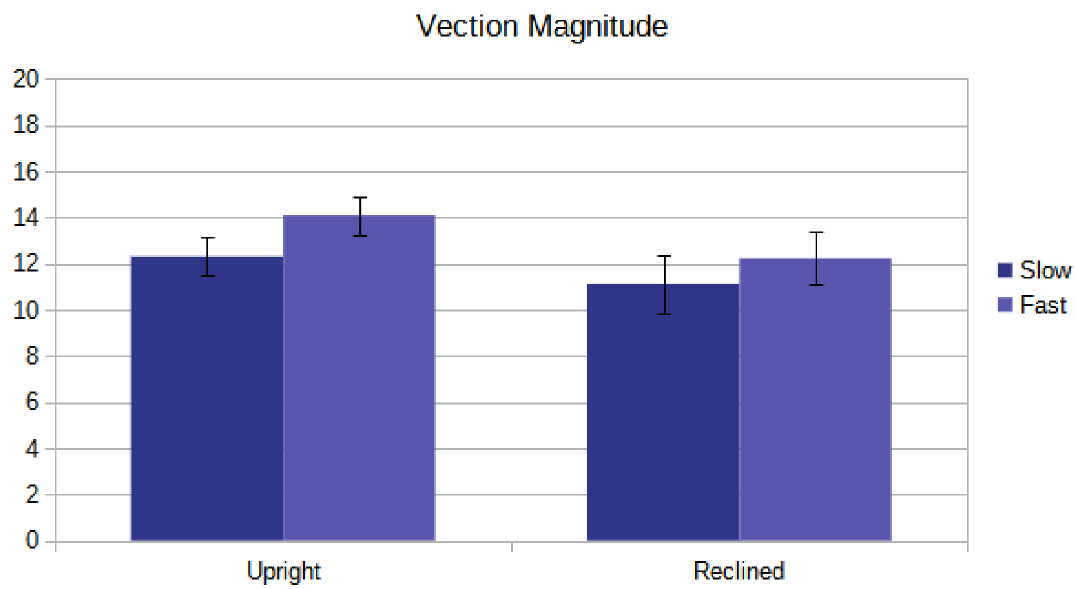

Figure 2. Bar graph showing vection magnitude ratings across posture and speed conditions in Experiment 1.

A two-way ANOVA did not reveal a significant main effect of posture or speed on vection magnitude.

Sickness

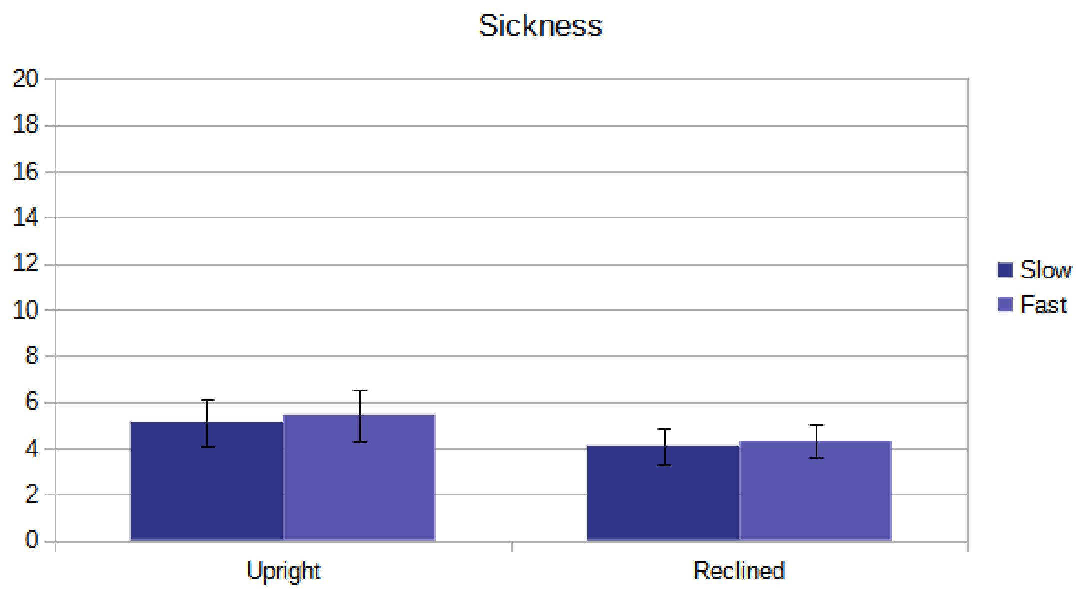

Figure 3. Bar graph showing sickness ratings across posture and speed conditions in Experiment 1.

A two-way ANOVA did not reveal a significant main effect of posture or speed on motion sickness severity.

Presence

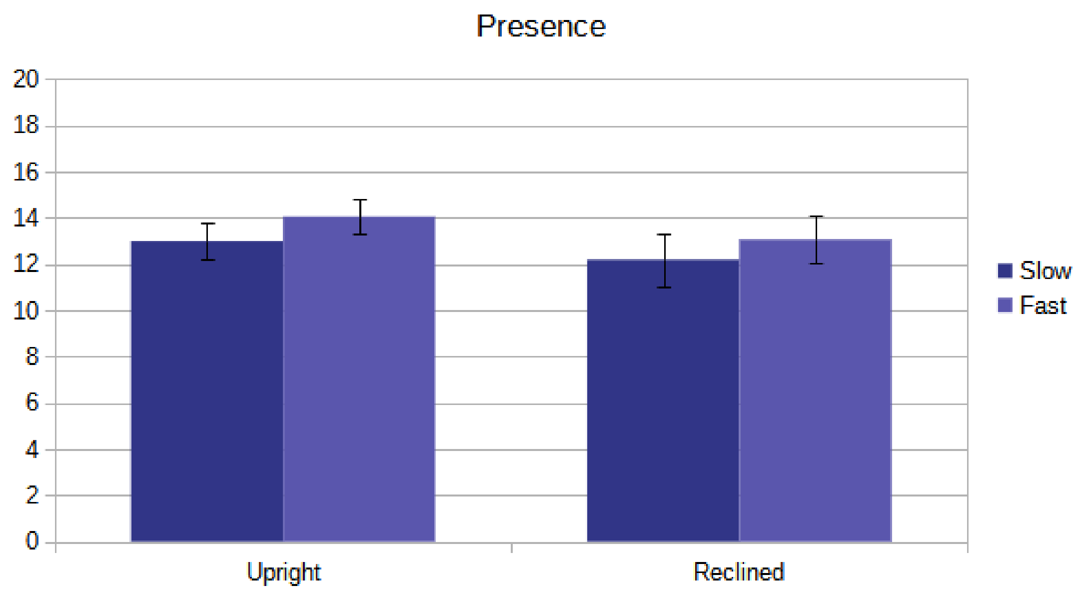

Figure 4. Bar graph showing presence ratings across posture and speed conditions in Experiment 1.

A two-way ANOVA did not reveal a significant main effect of posture or speed on presence ratings.

Discussion and Limitations

Experiment 1 suffered from several major limitations that may have contributed to the lack of significant findings. First of all, the sample size of 16 was relatively small. Second, the “slow” and “fast” conditions were relatively similar in speed (~90mph vs. ~120mph), which may have made the effect of speed negligible. Furthermore, each lap was driven separately, which may have introduced minor confounds (e.g. each lap may have approached turns slightly differently, with slightly different average speeds). Third, the audio remained on during all conditions of the experiment. It is possible that the engine sounds cued participants in unintended ways, influencing their perception of vection and presence. Additionally, the reclined position featured a camera adjustment along the pitch axis such that the road was parallel with the participants' eyesight. It is possible that the apparent misalignment between the real and virtual worlds in the reclined position confounded the effects of posture. Finally, the head rotation data proved to be non-viable due to recording errors. As such, analysis of the head rotation data for this experiment was not possible.

Chapter III – Experiment 2: Effect of posture, speed, and real/virtual world alignment on vection, sickness, and presence

In this experiment, we sought to address the limitations of Experiment 1 and investigate the effects of posture and virtual/real world alignment on the dependent variables. Since the camera was adjusted to match participants' viewpoint in the reclined posture, Experiment 1 failed to dissociate the effects of posture and world alignment. To address this, Experiment 2 introduced new conditions: a reclined posture condition in which the camera was unadjusted and an upright posture condition in which the camera was pitched 30 degrees downward. Both of these conditions result in a reduction of visual motion cues (as the participant is looking "upwards" relative to the track). These modifications allow for investigation of both real/virtual world alignment and visual cue availability.

Method

Participants

4 participants that dropped out of the experiment early due to motion sickness were excluded from all analyses. 10 participants that reported no sense of vection (e.g. a rating of 1 on the magnitude scale) for one or more laps were excluded from the vection onset time and vection duration analyses, but remained included in the vection magnitude, sickness, and presence analyses. The final dataset included 52 undergraduate students from the UCSC SONA subject pool (26 male, 26 female) between the ages of 18 and 26.

Design

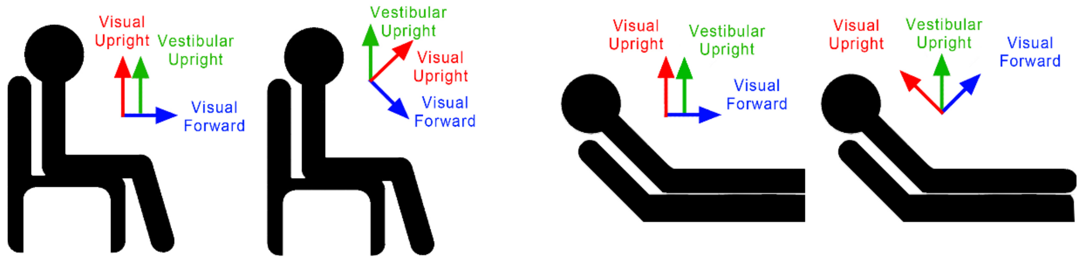

Figure 5. *Illustration of the four conditions in Experiment 2. From left to right, upright-aligned, upright-misaligned, reclined-aligned, and reclined-misaligned.*

This experiment employed a within-subjects, partially counterbalanced design similar to Experiment 1. In this experiment, we manipulated body posture (upright or reclined by 30 degrees), real/virtual world alignment (the virtual world is either aligned with the real world or pitched 30 degrees down/upwards in the upright/reclined conditions), and the speed of the driving simulation (across all conditions). It should be noted that the virtual/real world alignment can also be expressed as a difference in available visual cues: in the real-world-aligned upright condition, visual cue availability is higher, whereas in the real-world-aligned reclined condition, visual cue availability is reduced. In total, there were twelve trials across two main blocks, each containing two sub-blocks. The two main blocks manipulated body posture (upright or reclined, counterbalanced order). The sub-blocks manipulated the alignment of the real and virtual worlds. Within each sub-block, the stationary period was always experienced first, while the order of the following trials (full speed or half speed) was counterbalanced such that half the participants always experienced the half-speed lap first and half experienced the full-speed lap first.

Materials

Hardware and Software

Experiment 2 utilized the same software and hardware as Experiment 1.

Figure 6. Screenshot from the iRacing stimulus during a misaligned upright (or aligned reclined) lap (camera pitched 30 degrees upward).

Stimuli

Experiment 2 employed slightly different racetrack stimuli than the ones used in Experiment 1. Most notably, a different method for adjusting the speed of the lap was employed. Rather than driving four separate laps at different speeds, this experiment used one fast lap (average speed 120mph, top speed 140mph) that was either presented at full speed, half-speed (average speed 60mph, top speed 70mph), or paused/stationary (0mph). The stationary trials were used to establish a baseline for sickness and presence measures. Each lap was presented for exactly 60 seconds. This allowed for more consistent visual presentation of the stimuli. Additionally, the audio (e.g., engine sounds, gear-shifting, wind) was removed in this version of the experiment to improve consistency and eliminate sound as a confounding variable.

Procedure

Just as in Experiment 1, participants arrived, signed consent forms, then put on the head-mounted display with the help of a research assistant. They were then randomly assigned to a seating position (upright or reclined) which they maintained for the first main block of six trials, before switching to the other seating position. Within these main blocks, they were randomly assigned to a sub-block of three trials. Each block of six trials was broken into two sub-blocks of three trials each. The first trial of each sub-block was stationary, to establish a baseline sense of motion sickness and presence. The next two trials were presented in a counterbalanced order of the laps described in the Stimuli section (full speed, half speed). After each trial, the participant was asked to self-report vection magnitude (on a 1-20 scale), vection onset time (in seconds), vection duration (in seconds), motion sickness (1-20 scale), and presence (1-20 scale). Following the completion of the first main block, participants completed a midpoint survey assessing more detailed measures of vection, motion sickness, and presence. Then they completed the second main block in the alternate seating position (upright or reclined). Following the second block, the participants completed the same survey again followed by a demographic survey. Throughout all trials, rotational and positional data was recorded continuously.

Results

The following analyses utilized a five-way ANOVA that included three within-subjects factors (posture, alignment, and speed) and two between-subjects factors (gender and order).

Vection Magnitude

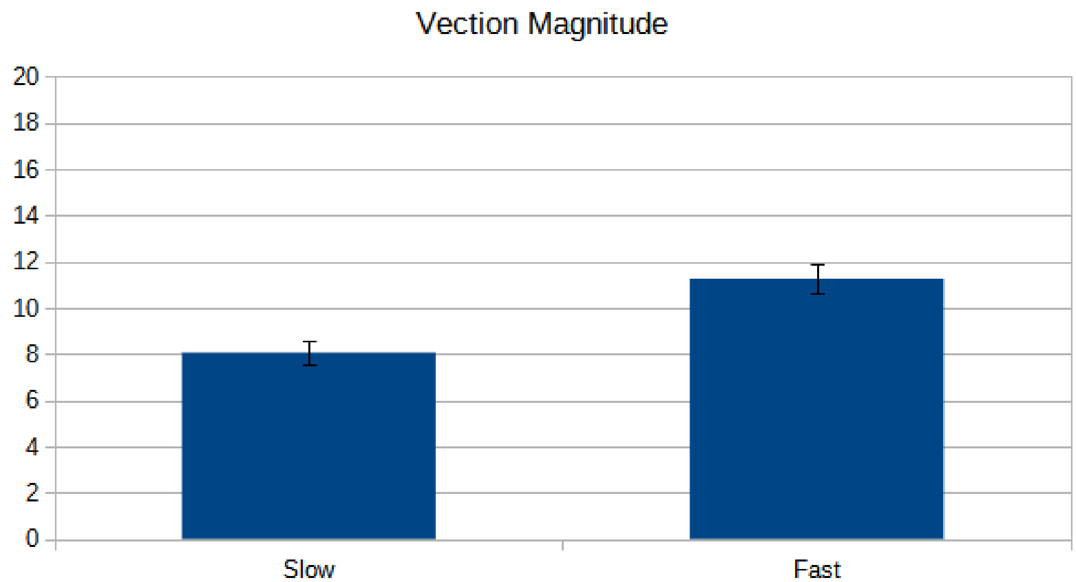

Figure 7. Bar graph showing vection magnitude ratings across speed conditions in Experiment 2.

A five-way ANOVA revealed a main effect of speed on vection magnitude ratings, such that the higher speed condition resulted in a more compelling sense of vection ($F = 78.05$, $p < .01$).

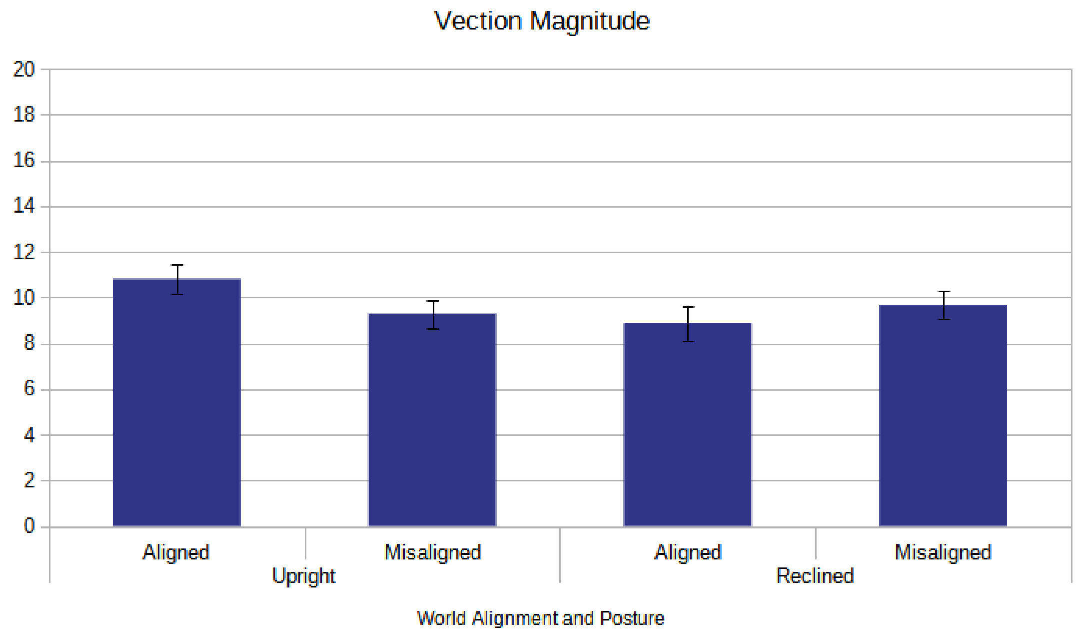

Figure 8. Bar graph showing vection magnitude ratings across visual cue availability conditions in Experiment 2.

Additionally, an interaction between posture and visual cue availability was revealed, such that vection was more compelling when visual cues were more available (e.g. in the upright-aligned condition and in the reclined-misaligned condition) (F = 9.02, p < .01).

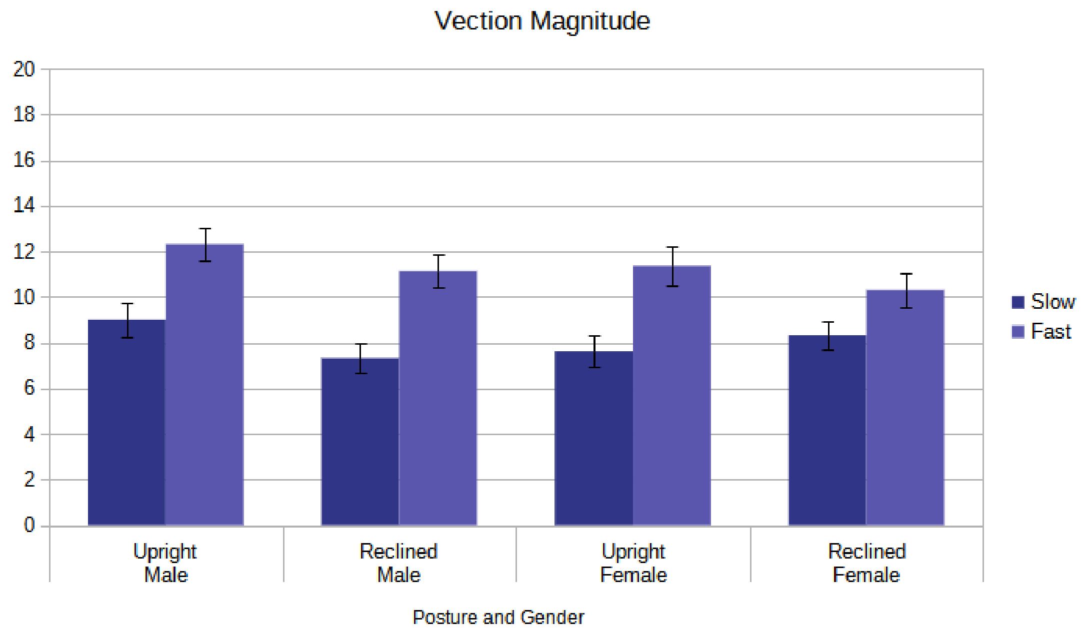

Figure 9. *Bar graph showing three-way interaction between posture, speed, and gender on vection magnitude ratings in Experiment 2.*

Finally, a three-way interaction between posture, speed, and gender was found, such that during the slow laps, vection magnitude ratings were higher in the upright position for men and higher in the reclined position for women, whereas during the fast laps, posture and gender had negligible effects on vection magnitude ratings (F = 7.17, p < .05).

Vection Onset Time

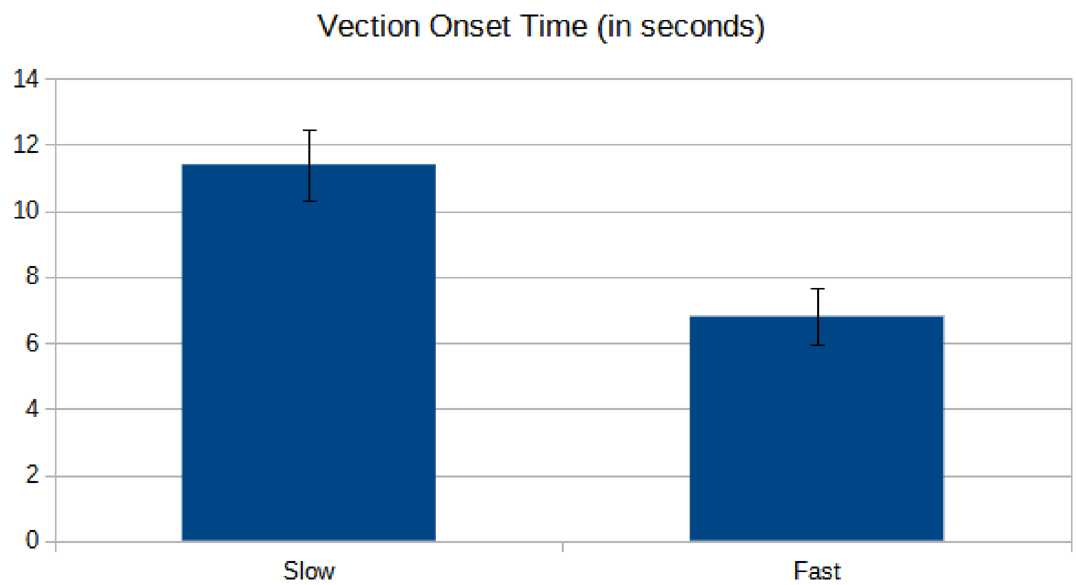

Figure 10. Bar graph showing vection onset time across speed conditions in Experiment 2.

A five-way ANOVA revealed a main effect of speed on vection onset time, such that the higher speed condition resulted in a faster onset ($F = 76.85$, $p < .01$).

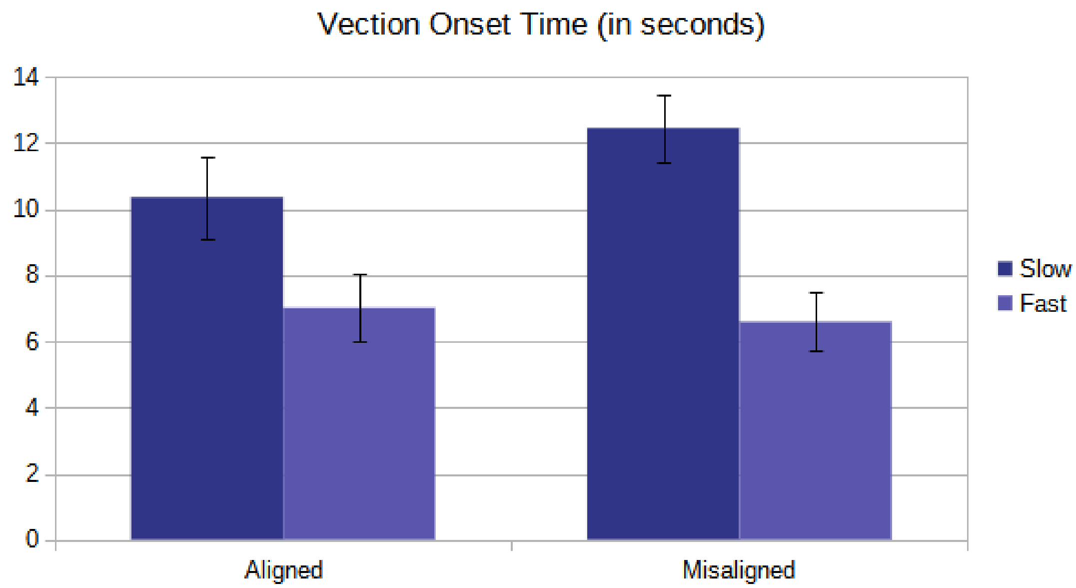

Figure 11. *Bar graph showing vection onset time across speed and alignment conditions in Experiment 2.*

A five-way ANOVA revealed a significant interaction between alignment and speed on vection onset time such that slow laps resulted in a comparatively slower onset time in the misaligned conditions than in the aligned conditions (onset times during the fast laps did significantly differ in response to alignment) ($F = 16.61$, $p < .01$). It should be noted that participants who reported at least one lap in which they did not experience vection (e.g. a vection magnitude rating of "1") were excluded from this analysis.

Vection Duration

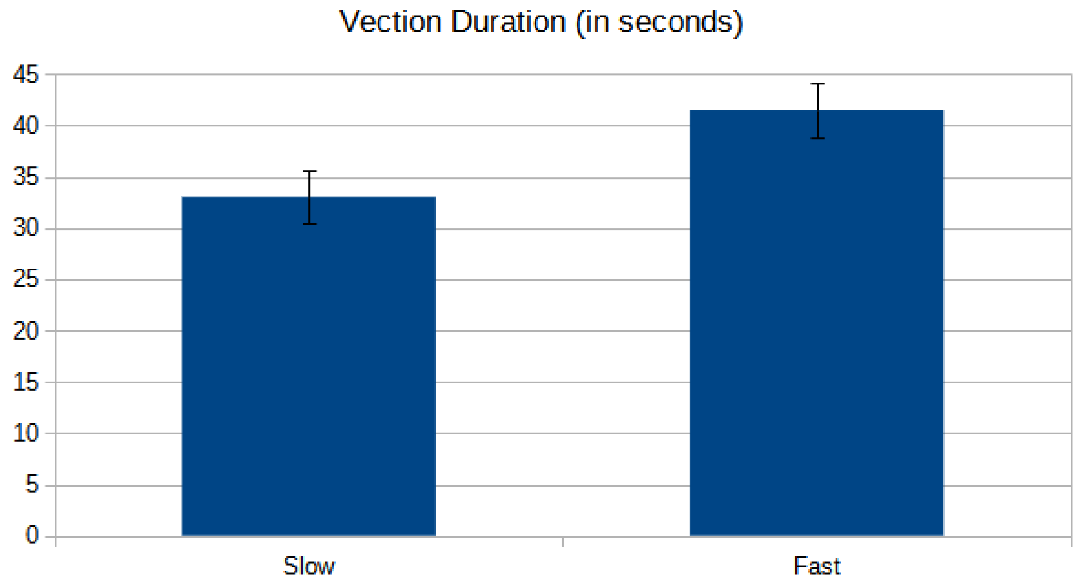

Figure 12. Bar graph showing vection duration across speed conditions in Experiment 2.

A five-way ANOVA revealed a main effect of speed on vection duration, such that the higher speed condition resulted in a longer vection duration ($F = 19.519$, $p < .01$). It should be noted that participants who reported at least one lap in which they did not experience vection (e.g. a vection magnitude rating of “1”) were excluded from this analysis.

Sickness

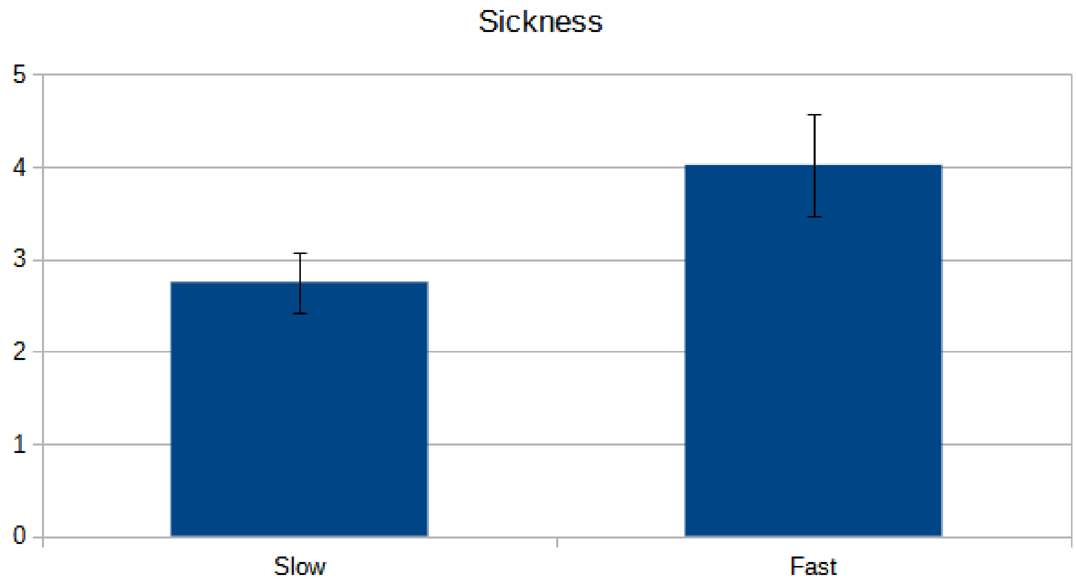

Figure 13. Bar graph showing sickness ratings across speed conditions in Experiment 2.

A five-way ANOVA revealed a main effect of speed on motion sickness ratings, such that high speed laps resulted in greater motion sickness severity (F = 15.02, $p < .01$).

__Sickness Order Effects__

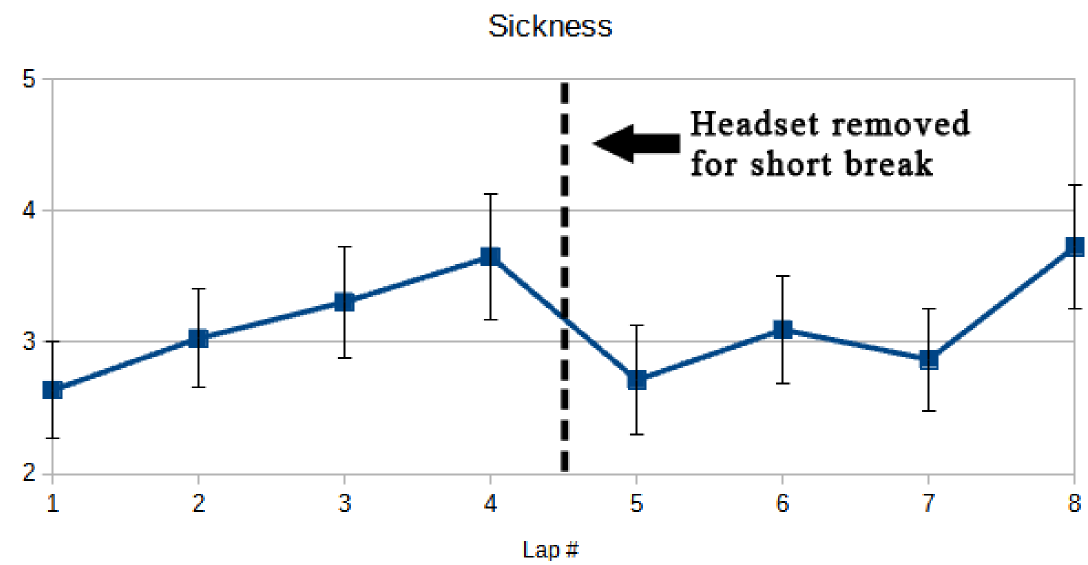

Figure 14. *Line graph showing sickness ratings over time in Experiment 2.*

A one-way ANOVA revealed a main effect of order on motion sickness ratings, such that participants get progressively sicker as the experiment goes on (with a noticeable dip between the fourth and fifth trials, during which the participants took off the headset and filled out a short questionnaire) ($F = 2.26$, $p < .05$). We measured whether sickness increases generally over time by conducting individual correlations between sickness and lap number, which did not result in a significant effect. We conducted a separate analysis looking at the first and second block separately. When examining the blocks separately, two t-tests revealed that sickness significantly increased over time in the first block ($t = 2.41$, $p < .05$) and the second block ($t = 2.24$, $p < .05$).

Presence

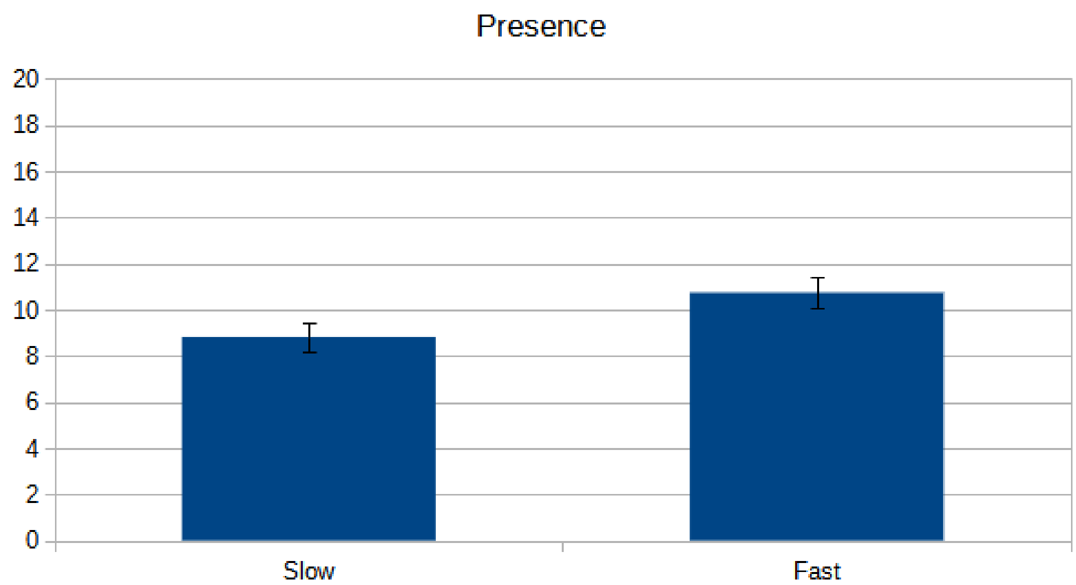

Figure 15. Bar graph showing presence ratings across speed conditions in Experiment 2.

A five-way ANOVA revealed a main effect of speed on presence ratings, such that the higher speed condition resulted in higher presence ratings ($F = 28.86$, $p < .01$).

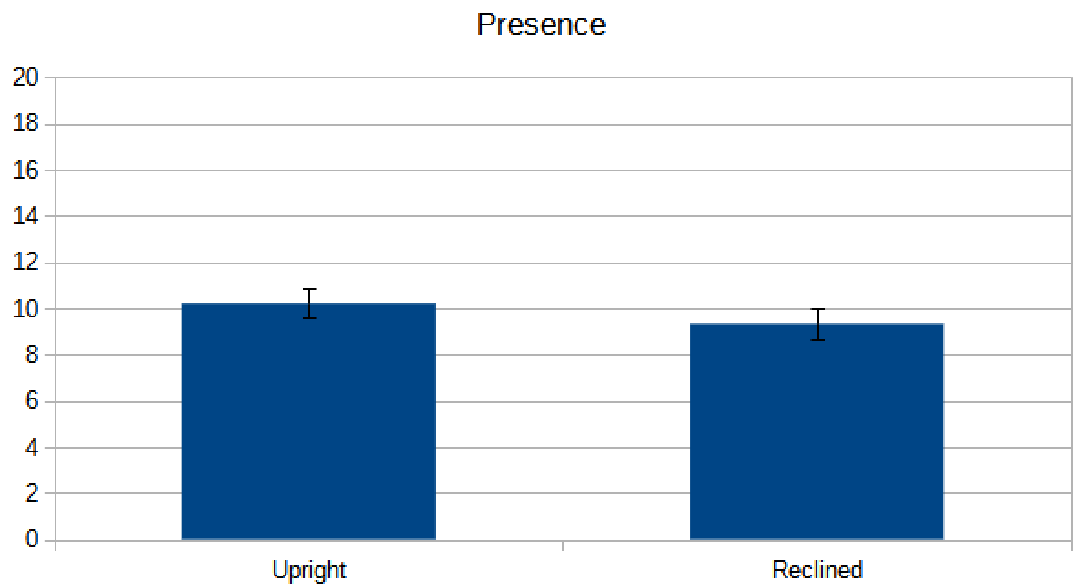

Figure 16. Bar graph showing presence ratings across posture conditions in Experiment 2.

A five-way ANOVA revealed a main effect of posture on presence ratings, such that the upright condition resulted in a stronger sense of presence ($F = 4.45$, $p < .05$)

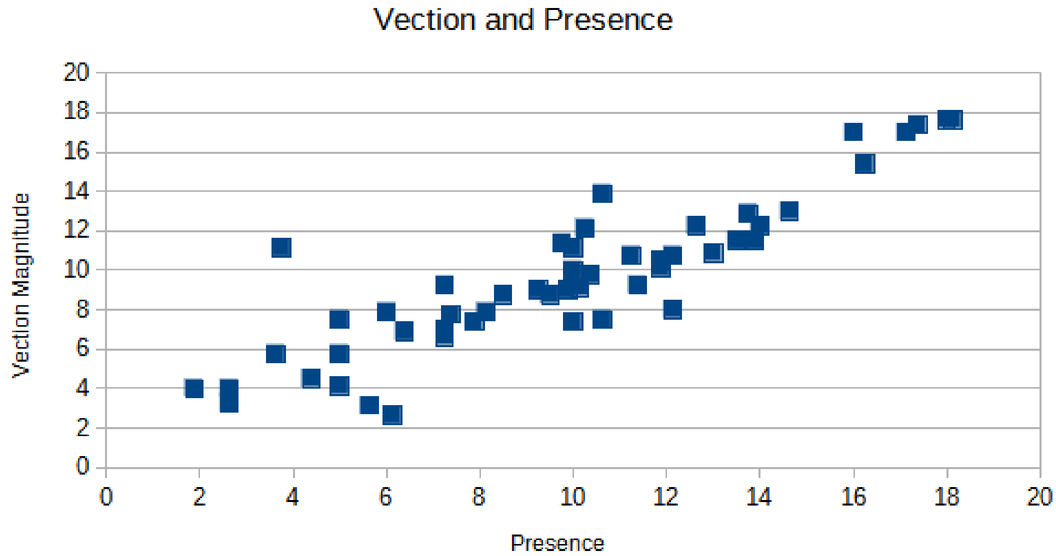

Figure 17. *Scatterplot showing a correlation between vection magnitude and presence ratings in Experiment 2, collapsed across conditions.*

A Pearson's *r* demonstrated that vection magnitude and presence had a positive correlation ($r = .89$, $p < .01$).

Head Rotation Absolute Velocity and Coherence as Dependent Variables

The data was recorded at 90Hz (i.e., 90 datapoints per second) and was broken into three axes: pitch, yaw, and roll. This data was analyzed in two ways: in terms of mean absolute velocity along each axis and in terms of the mean deviation from the center (the center being the participant's default viewpoint, facing forward at the beginning of the lap) along each axis. We began by plotting mean deviation from the center over time along each axis (Figure 18, Figure 19, and Figure 21). The blue bars represent one standard error of the mean, whereas the solid black line represents the mean deviation. Smaller blue bars represent more consistent head movements amongst participants.

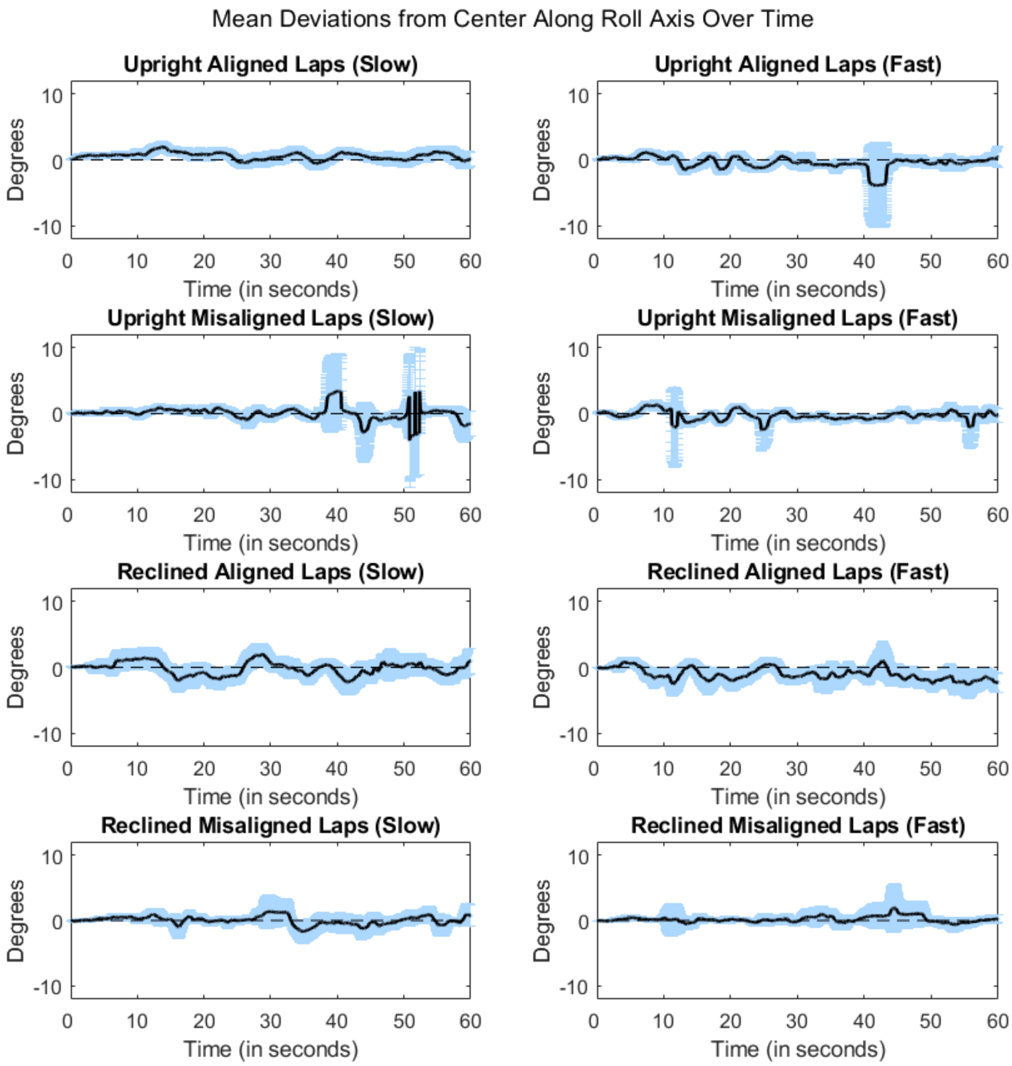

Figure 18. Plots of mean deviations from center along the roll axis over time across conditions in Experiment 2. Solid black lines denote the grand mean. Blue bars denote +/- 1 standard error of the mean.

Figure 18 revealed that head movement along the roll axis did not vary significantly over time, with participants tending to keep their heads centered along this axis for the duration of the experiment.

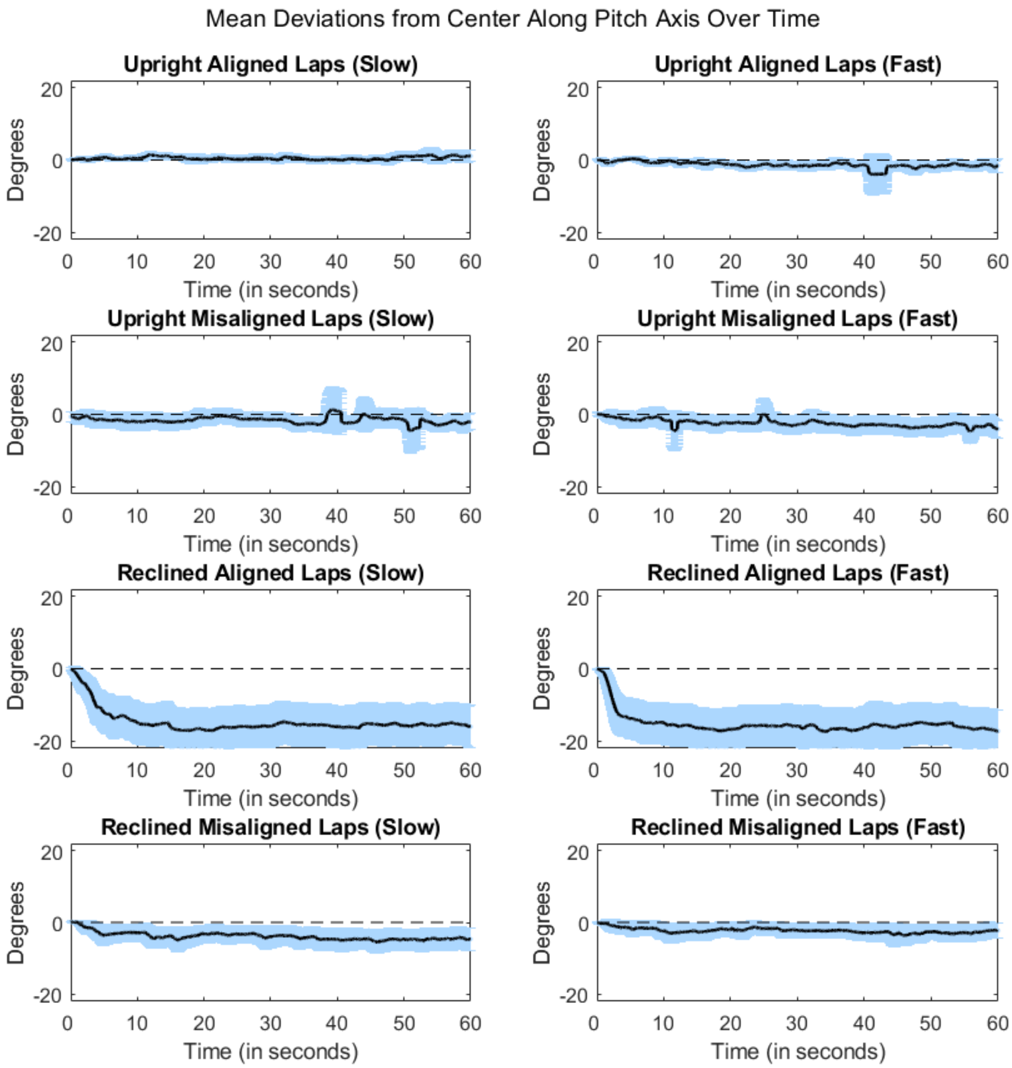

Figure 19. Plots of mean deviations from center along the pitch axis over time across conditions in Experiment 2. Solid black lines denote the grand mean. Blue bars denote +/- 1 standard error of the mean.

Figure 19 revealed that head movements along the pitch axis remained mostly consistent throughout the experiment, except for during the reclined-aligned laps. Note that the scale of Figure 19 has been adjusted to accommodate the larger range of motion along this axis. In these conditions, participants tended to point their heads downwards by as much as 15 degrees, presumably to compensate for the reduced visual cue availability. Note that in the upright-misaligned conditions (which also displayed reduced visual cue availability), participants still tended to point their heads downwards, but to a lesser degree (2-3 degrees) and with greater consistency. The large error bars (plotted in blue) indicate a large degree of variability amongst participants.

To quantify differences in coherence of head motion along the pitch axis across different conditions, we computed the mean and standard deviation of individual participants’ correlation to the mean head motion in each condition. The bar graph below (Figure 20) shows the mean correlations across the eight experimental conditions.

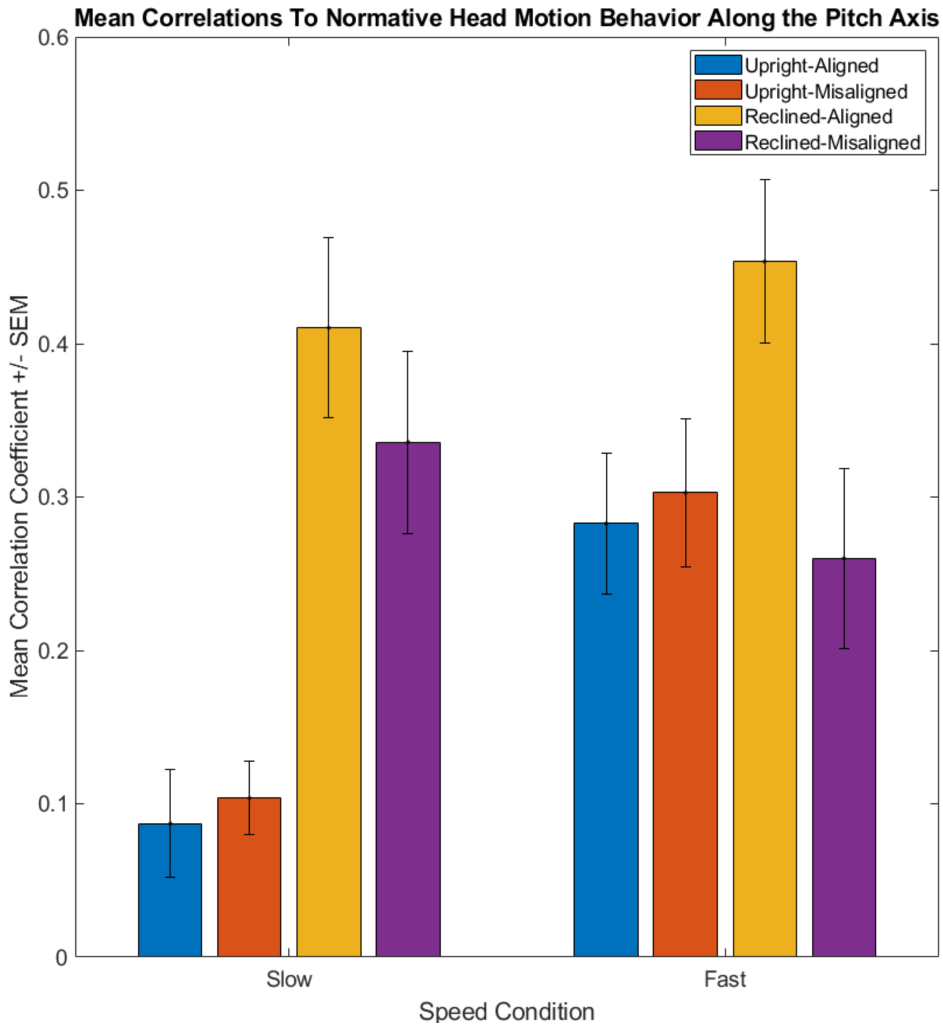

Figure 20. *Bar graph showing mean correlations to normative head motion behavior along the pitch axis across conditions in Experiment 2.*

Paired *t*-tests revealed that the correlations between individual pitch movements and the grand mean pitch movements in the slow reclined laps (*M* = .37, *SD* = .34) were significantly higher than in the slow upright laps (*M* = .10, *SD* = .15; *t* = 5.49, *p* < .01). Paired *t*-tests also revealed that correlations between individual pitch movements and the grand mean pitch movements in the fast reclined-aligned condition (*M* = .45, *SD* = .38) were significantly higher than in the fast upright-aligned condition (*M* = .28, *SD* = .33; $t = 2.61$, $p < .05$), the fast upright-misaligned condition (*M* = .30, *SD* = .35; $t = 2.04$, $p < .05$), and the reclined-misaligned condition (*M* = .26, *SD* = .42; $t = 2.19$, $p < .05$).

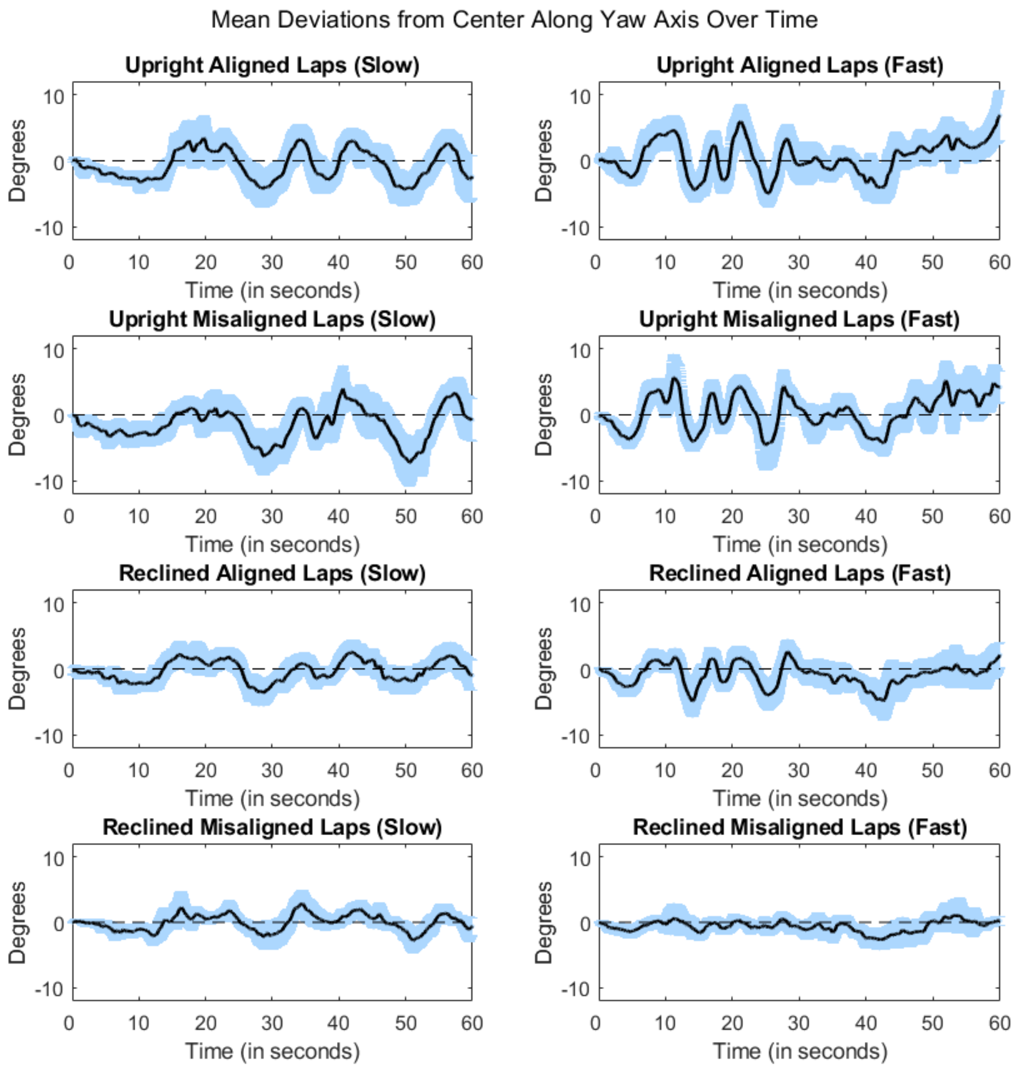

Figure 21. *Plots of mean deviations from center along the yaw axis over time across conditions in Experiment 2. Solid black lines denote the grand mean. Blue bars denote +/- 1 standard error of the mean.*

Figure 21 revealed that head movements along the yaw axis varied significantly over time. Participants tended to turn their heads left and right along the yaw axis in response to in-simulation turns that take place between the 10-50 second marks (in the slow laps) and the 5-25 seconds (in the fast laps). Note that the behavior of head turning over the course of the entire slow lap is similar to the behavior of head turning over the course of the first 30 seconds of the fast lap. The first half of the fast lap covers the same distance (and same turns) on the virtual track as the entirety of the slow lap because the fast laps are displayed at twice the speed of the slow laps.

As can be inferred from Figure 21, the average absolute velocity of head movements (measured in degrees/ms) along the yaw axis was lower in the reclined conditions (M = .02, SD = .02) compared to the upright conditions (M = .03, SD = .03; t = 4.22, $p < .01$). This can likely be attributed to the fact that it is slightly more difficult to move one's head/headset when reclined (as the back of the headset is pressed against the bed). The average absolute velocity of head movements along the yaw axis was also lower in the misaligned conditions (M = .02, SD = .03) compared to the aligned conditions (M = .03, SD = .02; t = 2.01, $p < .05$).

To quantify differences in coherence of head motion along the yaw axis across different conditions, we computed the mean and standard deviation of individual participants' correlation to the mean head motion in each condition. The bar graph below (Figure 22) shows the mean correlations across the eight experimental conditions.

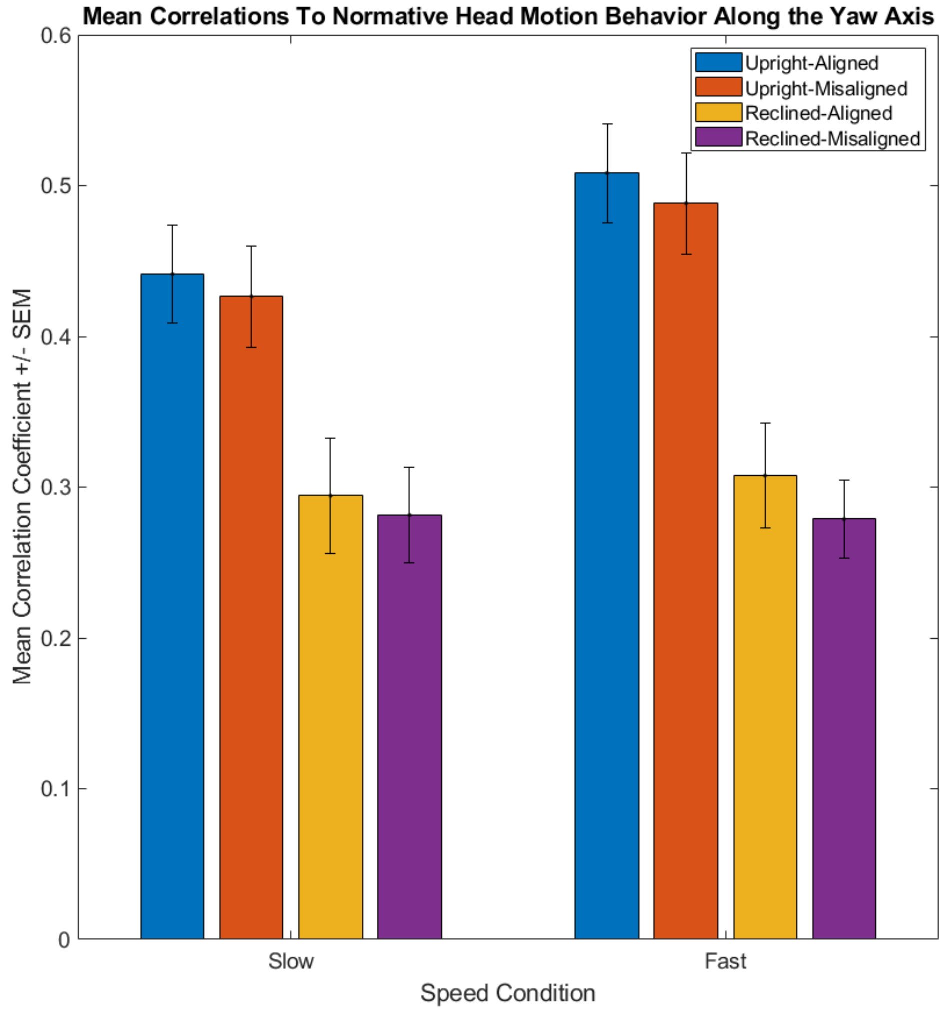

Figure 22. *Bar graph showing mean correlations to normative head motion behavior along the yaw axis across conditions in Experiment 2.*

Paired *t*-tests revealed that the correlations between individual yaw movements and the grand mean yaw movements in the slow upright laps (M = .43, SD = .21) were significantly higher than in the slow reclined laps (M = .29, SD = .20; t = 4.08, p < .01). Similarly, paired *t*-tests revealed that the correlations between individual yaw movements and the grand mean yaw movements in the fast upright laps (M = .50, SD = .21) were significantly higher than in the fast reclined laps (M =

.29, *SD* = .20; *t* = 6.30, *p* < .01).

The roll axis was omitted from coherence analyses because deviation along the roll axis did not vary significantly over time.

Head Rotation as a Predictor of Self-reported Dependent Variables

To treat head rotation as a predictor of self-reported dependent variables, we examined correlations between average absolute velocity along each axis and self-reported vection, sickness, and presence ratings.

Vection/Absolute Velocity Correlations	Pitch	Yaw	Roll
Upright-Aligned (Slow)	0.19 (p = 0.18)	0.06 (p = 0.66)	0.12 (p = 0.40)
Upright-Aligned (Fast)	0.10 (p = 0.49)	0.09 (p = 0.51)	0.04 (p = 0.79)
Upright-Misaligned (Slow)	**0.37 (p < 0.01)**	**0.37 (p < 0.01)**	**0.37 (p < 0.01)**
Upright-Misaligned (Fast)	**0.28 (p < 0.05)**	**0.39 (p < 0.01)**	**0.36 (p < 0.01)**
Reclined-Aligned (Slow)	0.12 (p = 0.38)	0.06 (p = 0.67)	0.04 (p = 0.76)
Reclined-Aligned (Fast)	0.10 (p = 0.48)	0.11 (p = 0.42)	0.06 (p = 0.66)
Reclined-Misaligned (Slow)	0.08 (p = 0.56)	0.12 (p = 0.40)	0.11 (p = 0.44)
Reclined-Misaligned (Fast)	0.09 (p = 0.52)	0.18 (p = 0.20)	0.16 (p = 0.26)

Table 1. Correlation coefficients between vection ratings and mean absolute velocity across conditions and axes in Experiment 2. Significant correlations shown in bold.

Table 1 shows that average absolute velocity of head movements along the pitch, yaw, and roll axes correlate positively with vection ratings in both the slow (r = .37, p < .01; r = .37, p < .01; r = .37, p < .01) and fast (r = .28, p < .05; r = .39, p < .01; r = .36, p < .01) upright-misaligned conditions.

Sickness/Absolute Velocity Correlations	Pitch	Yaw	Roll
Upright-Aligned (Slow)	-0.09 (p = 0.50)	-0.21 (p = 0.13)	-0.16 (p = 0.24)
Upright-Aligned (Fast)	0.11 (p = 0.42)	-0.13 (p = 0.34)	-0.10 (p = 0.47)
Upright-Misaligned (Slow)	0.02 (p = 0.89)	-0.14 (p = 0.31)	0.10 (p = 0.48)
Upright-Misaligned (Fast)	0.21 (p = 0.12)	0.06 (p = 0.65)	0.17 (p = 0.23)
Reclined-Aligned (Slow)	0.00 (p = 0.99)	-0.04 (p = 0.76)	-0.03 (p = 0.80)
Reclined-Aligned (Fast)	-0.10 (p = 0.48)	-0.17 (p = 0.22)	-0.12 (p = 0.39)
Reclined-Misaligned (Slow)	-0.16 (p = 0.25)	**-0.28 (p < 0.05)**	-0.21 (p = 0.14)
Reclined-Misaligned (Fast)	-0.06 (p = 0.67)	-0.05 (p = 0.72)	-0.09 (p = 0.51)

Table 2. Correlation coefficients between sickness ratings and mean absolute velocity across conditions and axes in Experiment 2. Significant correlations shown in bold.

Table 2 shows that average absolute velocity of head movements along the yaw axis correlated negatively with sickness ratings (r = -.28, p < .05).

Presence/Absolute Velocity Correlations	Pitch	Yaw	Roll
Upright-Aligned (Slow)	0.07 (p = 0.59)	-0.02 (p = 0.91)	0.02 (p = 0.90)
Upright-Aligned (Fast)	0.09 (p = 0.52)	0.11 (p = 0.44)	0.07 (p = 0.63)
Upright-Misaligned (Slow)	**0.29 (p < 0.05)**	**0.36 (p < 0.01)**	0.17 (p = 0.22)
Upright-Misaligned (Fast)	0.26 (p = 0.06)	**0.33 (p < 0.05)**	**0.29 (p < 0.05)**
Reclined-Aligned (Slow)	0.12 (p = 0.40)	0.01 (p = 0.97)	0.00 (p = 0.99)
Reclined-Aligned (Fast)	0.17 (p = 0.23)	0.04 (p = 0.80)	0.10 (p = 0.47)
Reclined-Misaligned (Slow)	0.18 (p = 0.20)	0.19 (p = 0.16)	0.15 (p = 0.28)
Reclined-Misaligned (Fast)	0.21 (p = 0.14)	0.25 (p = 0.07)	0.26 (p = 0.06)

Table 3. Correlation coefficients between presence ratings and mean absolute velocity across conditions and axes in Experiment 2. Significant correlations shown in bold.

Table 3 shows that average absolute velocity of head movements along the yaw axis correlated positively with presence ratings in the slow (r = .36, p < 0.01) and fast (r = .33, p < .05) upright-misaligned conditions. It also shows that average absolute velocity of head movements along the pitch axis correlated positively with presence ratings in the slow upright-misaligned condition (r = .29, p < .05), and that average absolute velocity of head movements along the roll axis correlated positively with presence ratings in the fast upright-misaligned condition (r = .29, p < .05).

We also examined correlations between conformity to normative head motion behavior along each axis and self-reported vection, sickness, and presence ratings.

Vection/Conformity Correlations	Pitch	Yaw	Roll
Upright-Aligned (Slow)	**0.29 (p < 0.05)**	0.23 (p = 0.10)	0.16 (p = 0.25)
Upright-Aligned (Fast)	-0.22 (p = 0.12)	**0.29 (p < 0.05)**	0.00 (p = 0.99)
Upright-Misaligned (Slow)	0.11 (p = 0.45)	0.21 (p = 0.13)	0.17 (p = 0.23)
Upright-Misaligned (Fast)	0.01 (p = 0.96)	**0.30 (p < 0.05)**	0.17 (p = 0.23)
Reclined-Aligned (Slow)	-0.02 (p = 0.91)	0.24 (p = 0.08)	0.01 (p = 0.96)
Reclined-Aligned (Fast)	0.08 (p = 0.57)	0.26 (p = 0.06)	0.08 (p = 0.57)
Reclined-Misaligned (Slow)	0.03 (p = 0.85)	0.14 (p = 0.31)	-0.09 (p = 0.53)
Reclined-Misaligned (Fast)	-0.16 (p = 0.25)	0.13 (p = 0.36)	**0.39 (p < 0.01)**

Table 4. Correlation coefficients between vection ratings and conformity to the mean head rotation behavior across conditions and axes in Experiment 2.

Conformity to the normative head movement behavior along the pitch axis had a significant positive correlation with vection ratings in the slow upright-aligned condition ($r = .29$, $p < .05$). Conformity to the normative head movement behavior along the yaw axis had a significant positive correlation with vection ratings in the fast upright-aligned ($r = .29$, $p < .05$) condition and the fast upright-misaligned condition ($r = .30$, $p < .05$). Conformity to the normative head movement behavior along the roll axis had a significant positive correlation with vection ratings in the fast reclined-misaligned condition ($r = .39$, $p < .01$).

Sickness/Conformity Correlations	Pitch	Yaw	Roll
Upright-Aligned (Slow)	0.08 (*p* = 0.60)	0.07 (*p* = 0.64)	0.17 (*p* = 0.24)
Upright-Aligned (Fast)	-0.13 (*p* = 0.37)	-0.08 (*p* = 0.59)	0.14 (*p* = 0.32)
Upright-Misaligned (Slow)	0.03 (*p* = 0.86)	0.01 (*p* = 0.96)	-0.03 (*p* = 0.83)
Upright-Misaligned (Fast)	0.06 (*p* = 0.66)	-0.18 (*p* = 0.21)	-0.02 (*p* = 0.87)
Reclined-Aligned (Slow)	0.05 (*p* = 0.73)	0.05 (*p* = 0.75)	0.18 (*p* = 0.21)
Reclined-Aligned (Fast)	0.16 (*p* = 0.25)	-0.15 (*p* = 0.28)	-0.05 (*p* = 0.72)
Reclined-Misaligned (Slow)	0.25 (*p* = 0.07)	0.01 (*p* = 0.94)	**-0.37 (*p* < 0.01)**
Reclined-Misaligned (Fast)	0.04 (*p* = 0.76)	-0.03 (*p* = 0.85)	-0.02 (*p* = 0.87)

Table 5. Correlation coefficients between sickness ratings and conformity to the mean head rotation behavior across conditions and axes in Experiment 2. Significant correlations shown in bold.

Conformity to the normative head movement behavior along the roll axis had a significant negative correlation with sickness ratings in the fast reclined-misaligned condition ($r = -.37$, $p < .01$).

Presence/Conformity Correlations	Pitch	Yaw	Roll
Upright-Aligned (Slow)	**0.30 (*p* < 0.05)**	0.16 (*p* = 0.26)	-0.09 (*p* = 0.52)
Upright-Aligned (Fast)	-0.23 (*p* = 0.10)	**0.30 (*p* < 0.05)**	0.09 (*p* = 0.53)
Upright-Misaligned (Slow)	0.05 (*p* = 0.70)	0.15 (*p* = 0.29)	0.17 (*p* = 0.23)
Upright-Misaligned (Fast)	0.04 (*p* = 0.80)	0.17 (*p* = 0.24)	0.16 (*p* = 0.25)
Reclined-Aligned (Slow)	0.01 (*p* = 0.97)	0.24 (*p* = 0.09)	-0.06 (*p* = 0.66)
Reclined-Aligned (Fast)	0.08 (*p* = 0.57)	**0.38 (*p* < 0.01)**	0.11 (*p* = 0.46)
Reclined-Misaligned (Slow)	0.01 (*p* = 0.95)	0.25 (*p* = 0.08)	0.11 (*p* = 0.46)
Reclined-Misaligned (Fast)	-0.11 (*p* = 0.44)	0.16 (*p* = 0.26)	**0.37 (*p* < 0.01)**

Table 6. Correlation coefficients between presence ratings and conformity to the mean head rotation behavior across conditions and axes in Experiment 2. Significant correlations shown in bold.

Conformity to the normative head movement behavior along the pitch axis had a significant positive correlation with presence ratings in the slow upright-aligned condition ($r = .30$, $p < .05$). Conformity to the normative head movement behavior along the yaw axis had a significant positive correlation with presence ratings in the fast upright-aligned ($r = .30$, $p < .05$) condition and the fast reclined-aligned condition ($r = .38$, $p < .01$). Conformity to the normative head movement behavior along the roll axis had a significant positive correlation with presence ratings in the fast reclined-misaligned condition ($r = .37$, $p < .01$).

Non-conformity to the mean was considered as a possible disqualifying factor for some participants, but ultimately rejected given that the primary analyses returned the same results even with the outlying participants excluded.

Discussion

The results demonstrate that speed had a significant effect on all dependent variables. In the high-speed condition, participants felt more present in the virtual environment, experienced higher levels and rates of motion sickness, and found their sense of vection to be more compelling. Additionally, vection experiences began sooner and lasted longer during the fast conditions.

The effects of speed on vection are congruent with literature on the relationship between stimulus velocity and vection magnitude, onset time, and duration. It should be noted that participants, when asked to report vection magnitude, were instructed not to simply rate the perceived speed of their illusory self-motion, but rather *how compelling* that experience was. It should also be noted that the magnitude of the illusion did not scale proportionally with the stimulus velocity. The fast condition was presented at twice the average speed of the slow condition, but the mean vection magnitude rating was only 1.4x stronger in the fast condition.

The effect of speed on sickness is also congruent with the literature on simulator sickness and sensory conflict theory. At higher speeds, there should be a greater incongruence between vestibular motion cues (which remain static throughout the experiment) and visual motion cues, thus owing to a greater incidence and severity of motion sickness among the participants.

Given the fact that the virtual environment was a race track (as opposed to a standard highway or street), it would follow that presence (which is closely tied to a sense of realism) was higher in the high speed conditions, since racing is generally associated with the experience of driving well above 60mph.

Upright posture resulted in a stronger sense of presence, which is most likely due to the fact that most driving experiences in real life are experienced in the upright position. As such, it stands to reason that the upright position felt more realistic and familiar, hence the higher ratings of presence. Surprisingly, posture did not have a significant effect on vection magnitude or sickness. In particular, an effect on sickness due to the reduced impact of vestibular cues in the reclined position was predicted (but not found). Postural instability theory claims that simulator sickness often arises from a diminished ability to adjust one’s posture in response to visual or vestibular cues. As such, it was predicted that in the reclined condition (where posture is more restricted than the upright condition), participants would experience a lower incidence and severity of motion sickness. One possible explanation for this lack of effect is that the difference in postural control across upright and reclined positions was negligible. A future study including standing (where posture is much harder to control, compared to when sitting or lying down) and fully reclined conditions could help address this limitation and determine the degree to which postural stability/control contributes to motion sickness, if at all.

Head rotation analyses demonstrated that head movement velocity across all three axes correlated positively with vection magnitude ratings, but only in the upright-misaligned conditions. The direction of this effect as well as its mechanism remains unclear. It is possible that moving one’s head at a higher velocity evokes more compelling feelings of vection when the virtual world is tilted 30 degrees downwards from center, but it is also possible that more compelling feelings of vection prompt higher velocity head movements to account for perceived self-motion. Perhaps the downward tilting of the world makes the track feel more "downhill," thus facilitating affordances of illusory self-motion. This finding warrants further investigation. Head movement velocity along the yaw axis also seemed to correlate positively with presence ratings, but only in the upright-misaligned conditions. Again, the direction and mechanism for this effect are both unclear. It is possible that the same mechanism that drove the vection/head rotation velocity effect also drove the effect on presence. Perhaps it is easier to immerse oneself when the virtual world is perceived as downhill, allowing for head movements along the yaw axis to have a greater effect.

There were several other correlations scattered across conditions and variables, but these should be taken with a grain of salt. The correlation tables were not Bonferroni-corrected for multiple measurements, so it may be specious to make grand conclusions based on these seemingly one-off correlations.

The most notable finding among the head rotation analyses was the discovery of normative head rotation behavior along the yaw axis. Participants clearly turned their heads to anticipate and/or respond to the turning of the virtual car around the track. Not only does this demonstrate the immersive power of the simulation (in that participants moved their heads to account for vestibular cues that were not present), but it also shows that head rotation behavior can be very consistent across participants when presented with the appropriate stimuli. This finding certainly warrants further investigation into the relationship between conformity to mean head rotation behavior and other experiential phenomena.

Limitations

The decision to allow participants to move their head freely may have reduced the impact of the independent variables. This decision was made in order to observe naturalistic head movements among participants during the presentation of the stimuli. However, it is possible that instructing participants to remain relatively still could have yielded more noticeable effects of posture and world alignment on the dependent variables.

Another major limitation was the lack of a fully-reclined or fully-standing postural condition. In order to truly address the influence of postural instability, more extreme manipulations of posture must be employed. Unfortunately, iRacing only allows for a maximum of 30 degrees of adjustment along the pitch axis, which eliminated the possibility of presenting laps fully reclined. Fully-standing conditions were excluded from the experimental design due to concerns that participants might lose their balance. Furthermore, a standing posture is inconsistent with the ecological experience of driving/riding in a racecar.

Chapter IV – Experiment 3: Effect of motion cue type (expanding, contracting, or translational) on vection, sickness, and presence

Method

Participants

3 participants that dropped out of the experiment early due to motion sickness were excluded from all analyses. 6 participants that reported no sense of vection (e.g. a rating of 1 on the magnitude scale) for one or more laps were excluded from the vection onset time and vection duration analyses, but remained included in the vection magnitude, sickness, and presence analyses. The final dataset included 36 undergraduate students from the UCSC SONA subject pool (15 male, 21 female) between the ages of 18 and 41.

Design

This experiment employed a within-subjects, partially counterbalanced design similar to Experiments 1 and 2. In this experiment, we manipulated the type of motion cues the participant was exposed to (expanding cues, contracting cues, or cues that translate from left to right), and the speed of the driving simulation (across all conditions). In the expanding and contracting conditions, the participant is facing out the front of the virtual car, but the direction of the car's movement is manipulated (e.g. driving forward in the case of the expanding cues, driving in reverse in the case of the contracting cues). In the translational condition, the participant is turned 90 degrees to the right as the car moves forward.

Every participant experienced all three facing direction blocks in a counterbalanced order. Speed order was kept consistent within each participant (e.g. slow laps first in each block or fast laps first in each block) and counterbalanced across conditions.

The three main blocks manipulated motion cue direction in a counterbalanced order. Within each block, the stationary period was always experienced first, while the order of the following trials (full speed or half speed) was counterbalanced such that half the participants always experienced the half speed lap first and half experienced the full-speed lap first.

Materials

Hardware and Software

Experiment 3 utilized the same software and hardware as Experiments 1 and 2.

Stimuli

Experiment 3 utilized the same stimuli (e.g. same lap recordings) as Experiment 2. The different motion cue conditions were manipulated as follows: the expanding cue conditions were functionally the same as the upright-aligned conditions in Experiment 2, the contracting cue conditions consisted of the same laps played in reverse, and the translational cue conditions involved rotating the in-game camera by 90 degrees along the yaw axis (then playing the standard forward-driving laps while the participant faced out the right side of the car). The three conditions of the experiment are illustrated in Figure 23.

Figure 23. *Figure illustrating the three motion cue conditions in Experiment 3. Arrows denote the direction of motion cues relative to the participant's viewpoint.*

Procedure

Just as in Experiment 2, participants arrived, signed consent forms, then put on the head-mounted display with the help of a research assistant. They were then assigned to one of three motion cue conditions (expanding, contracting, or translational) which they maintained for the first block of three trials. The first trial of each block was always stationary, to establish a baseline sense of motion sickness and presence. The next two trials were presented in a counterbalanced order of the laps referenced in the Stimuli section (full speed, half speed). During all trials, participants were instructed to look forward (relative to the real world, not the virtual world), but their head was not physically constrained in any way. After each trial, the participant was asked to self-report vection magnitude (on a 1-20 scale), vection onset time (in seconds), vection duration (in seconds), motion sickness (1-20 scale), and presence (1-20 scale). Following the completion of all three blocks, participants completed a survey assessing more detailed measures of vection, motion sickness, and presence, as well as demographic information.

Results

The following analyses utilized a four-way ANOVA that included two within-subjects factors (motion cueing direction and speed) and two between-subjects factors (gender and order).

Vection Magnitude

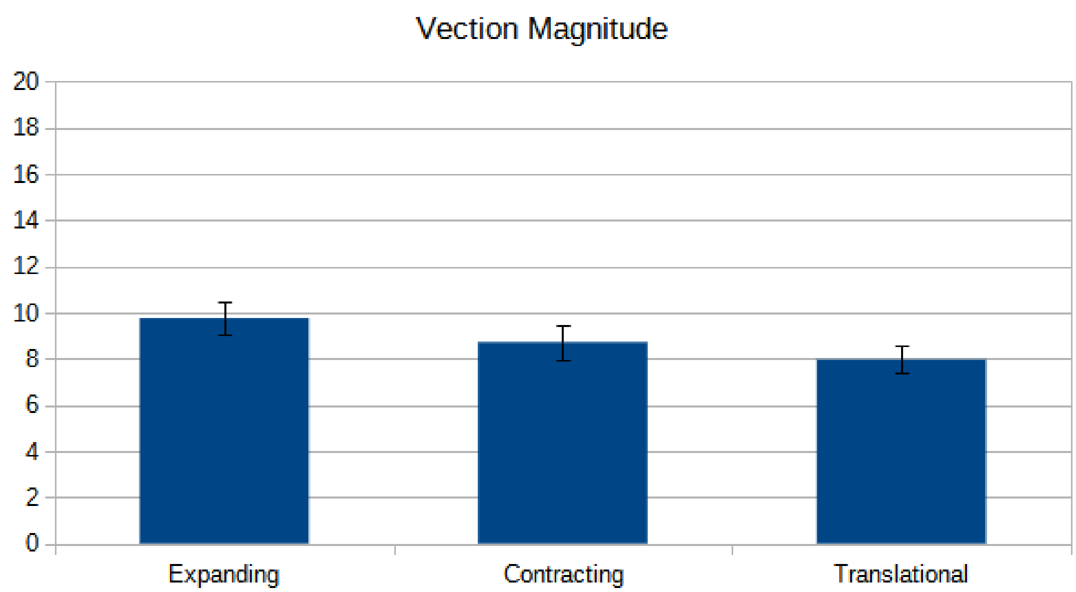

Figure 24. A bar graph showing vection magnitude ratings across motion cue direction conditions in Experiment 3.

A two-way ANOVA revealed a main effect of motion cue direction on vection magnitude, such that expanding cues resulted in a more compelling sense of vection than contracting or translational cues, and that contracting cues resulted in a more compelling sense of vection than translational cues (F = 3.35, p < .05).

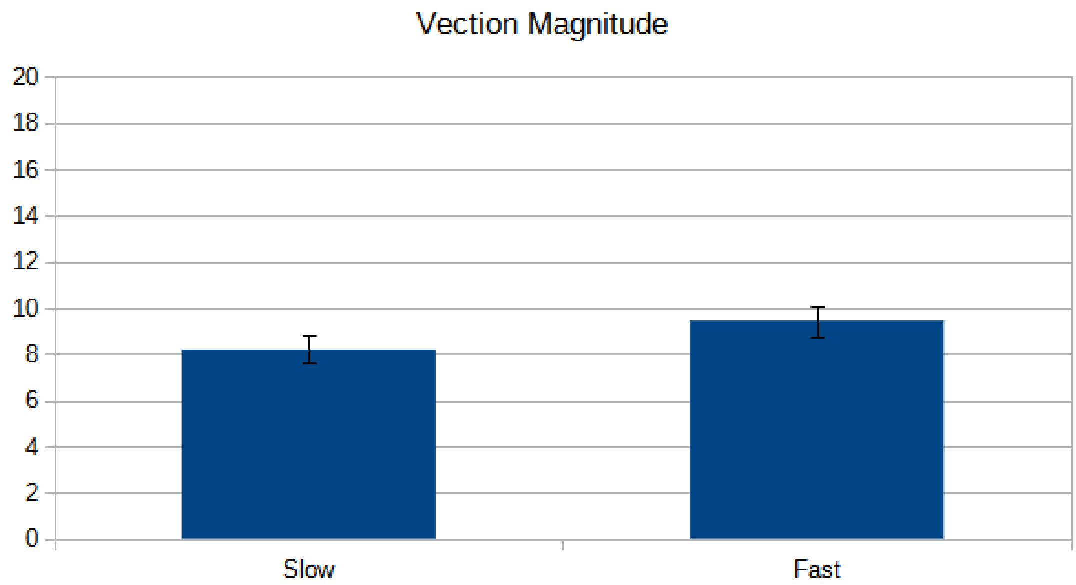

Figure 25. *Bar graph showing vection magnitude ratings across speed conditions in Experiment 3.*

A two-way ANOVA revealed a main effect of speed on vection magnitude, such that the fast laps resulted in a more compelling sense of vection (F = 6.32, p < .05).

Vection Onset Time

Two-way ANOVAs did not reveal any significant effects on vection onset time.

Vection Duration

Two-way ANOVAs did not reveal any significant effects on vection duration.

Sickness

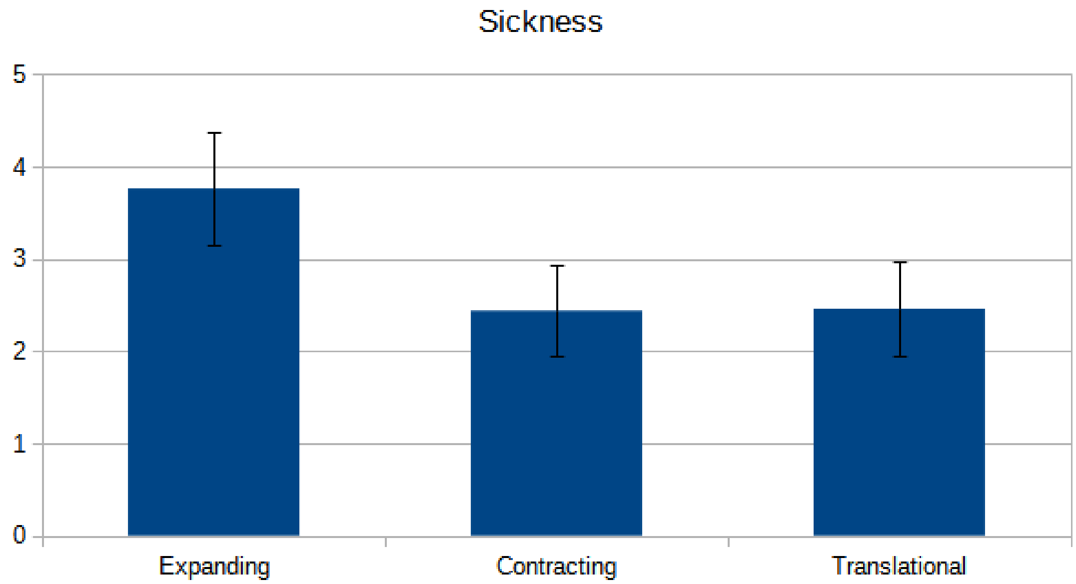

Figure 26. A bar graph showing sickness ratings across motion cue direction conditions in Experiment 3.

A two-way ANOVA revealed a main effect of motion cue direction on motion sickness ratings, such that the expanding cue condition resulted in a greater motion sickness severity than the contracting and translational cue conditions ($F = 5.52$, $p < .01$).

Sickness Order Effects

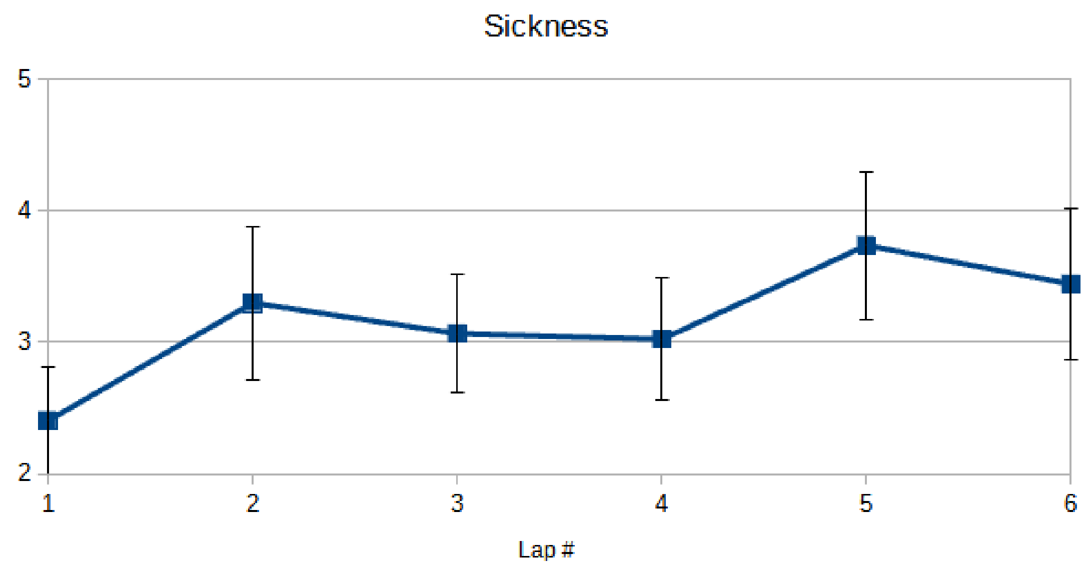

Figure 27. Line graph showing sickness ratings over time in Experiment 3.

A one-way ANOVA did not reveal a significant effect of order on motion sickness severity ($F = 1.62$, $p = .16$). Nevertheless, a t-test of individual slopes of sickness over time revealed that sickness increased significantly over time ($t = 2.32$, $p < .05$).

Presence

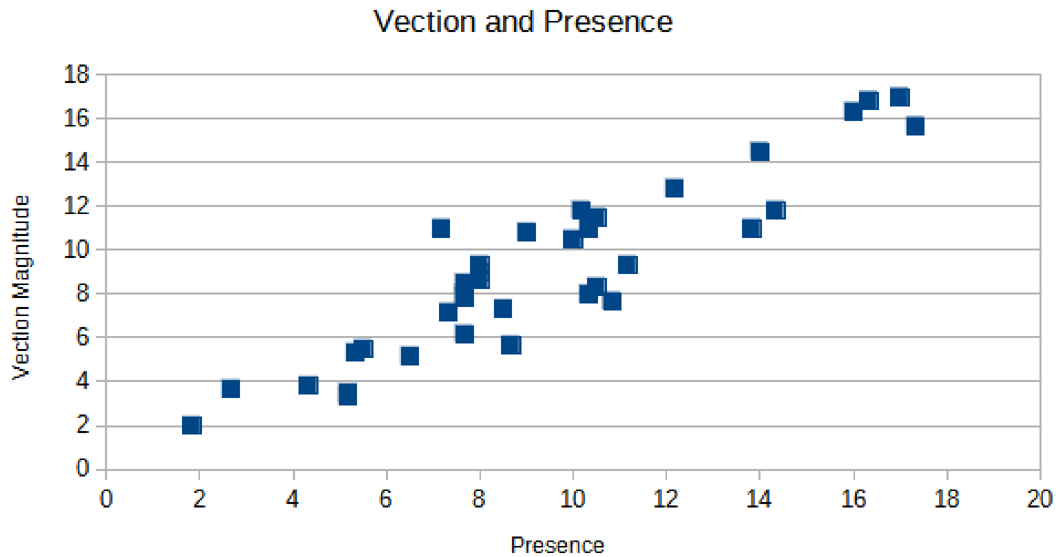

Figure 28. Scatterplot showing a correlation between vection magnitude and presence ratings in Experiment 3, collapsed across conditions.

Two-way ANOVAs did not reveal any significant effects on presence ratings from the independent variables. However, just as in Experiment 2, a Pearson's r indicated that vection magnitude and presence ratings were positively correlated (r = .92, $p < .01$).

Head Rotation Absolute Velocity and Coherence as Dependent Variables

Head rotation absolute velocity and coherence were analyzed in the same way as Experiment 2. To treat head rotation as a dependent variable, we started by plotting the mean deviation from center along each axis across conditions over time (Figure 29, Figure 30, and Figure 31). It should be noted that participants were instructed to look straight ahead (relative to their seating) throughout all conditions. Their head movement was not physically restricted. Nevertheless, participants still tended to move their heads slightly in response to the stimuli.

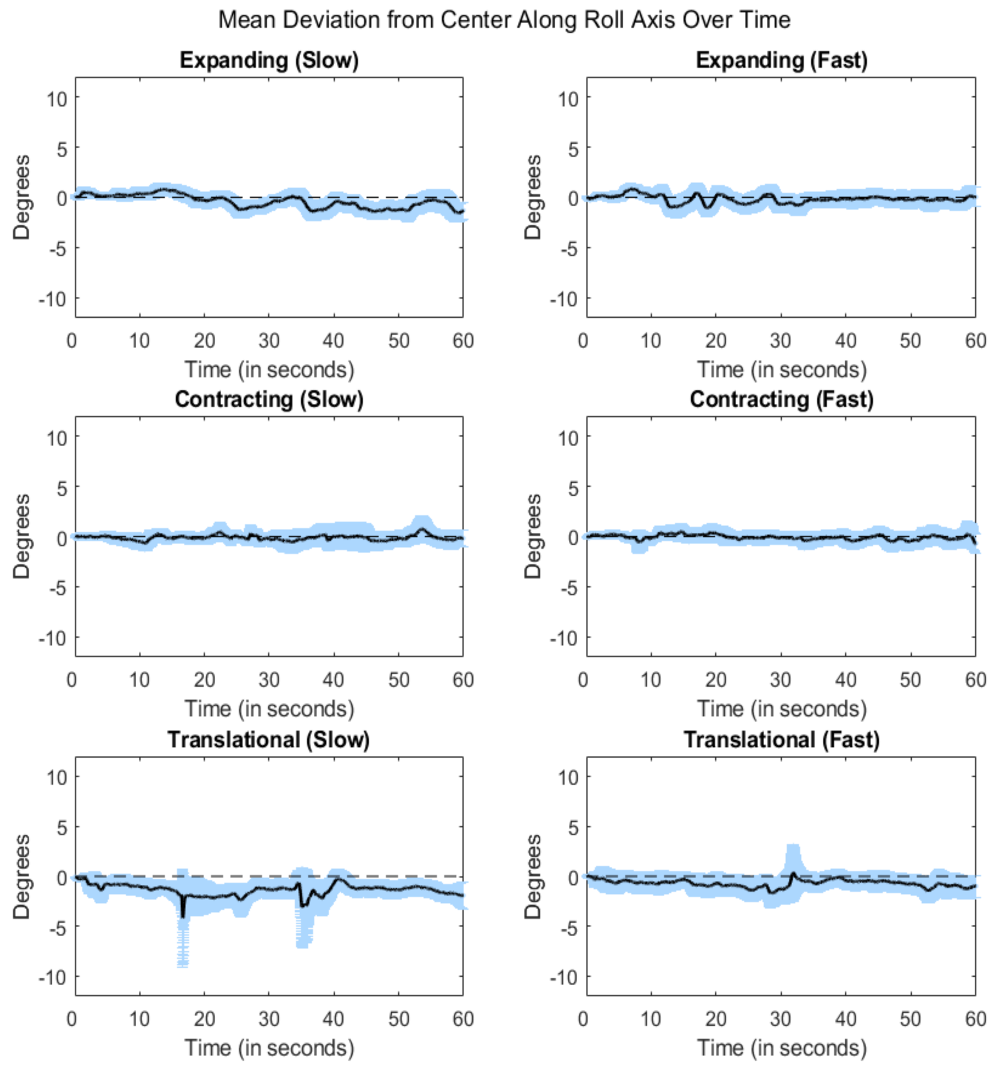

Figure 29. Plots of mean deviations from center along the roll axis over time across conditions in Experiment 3. Solid black lines denote the grand mean. Blue bars denote +/- 1 standard error of the mean.

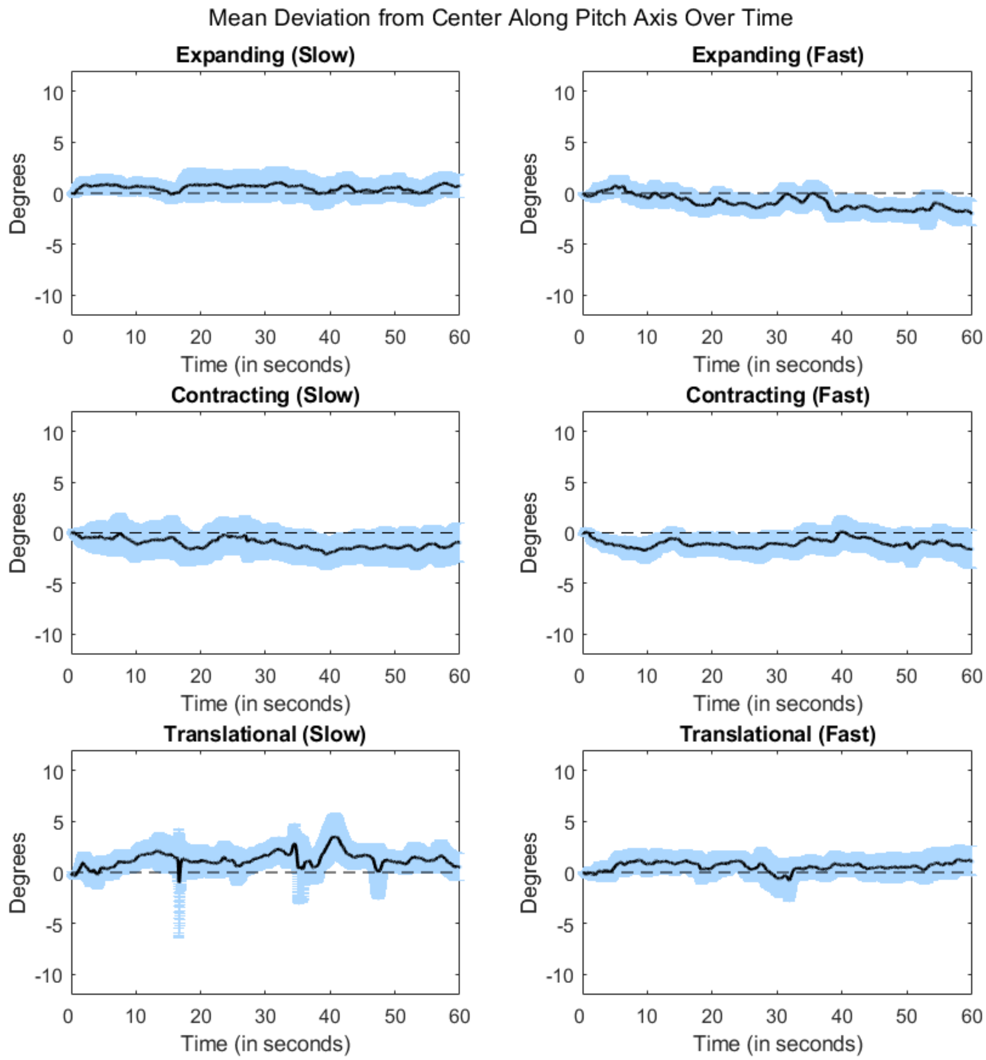

Figure 30. Plots of mean deviations from center along the pitch axis over time across conditions in Experiment 3. Solid black lines denote the grand mean. Blue bars denote +/- 1 standard error of the mean.

These plots reveal that head movement along the pitch and roll axes did not vary significantly over time, with most participants keeping their heads centered along these axes.

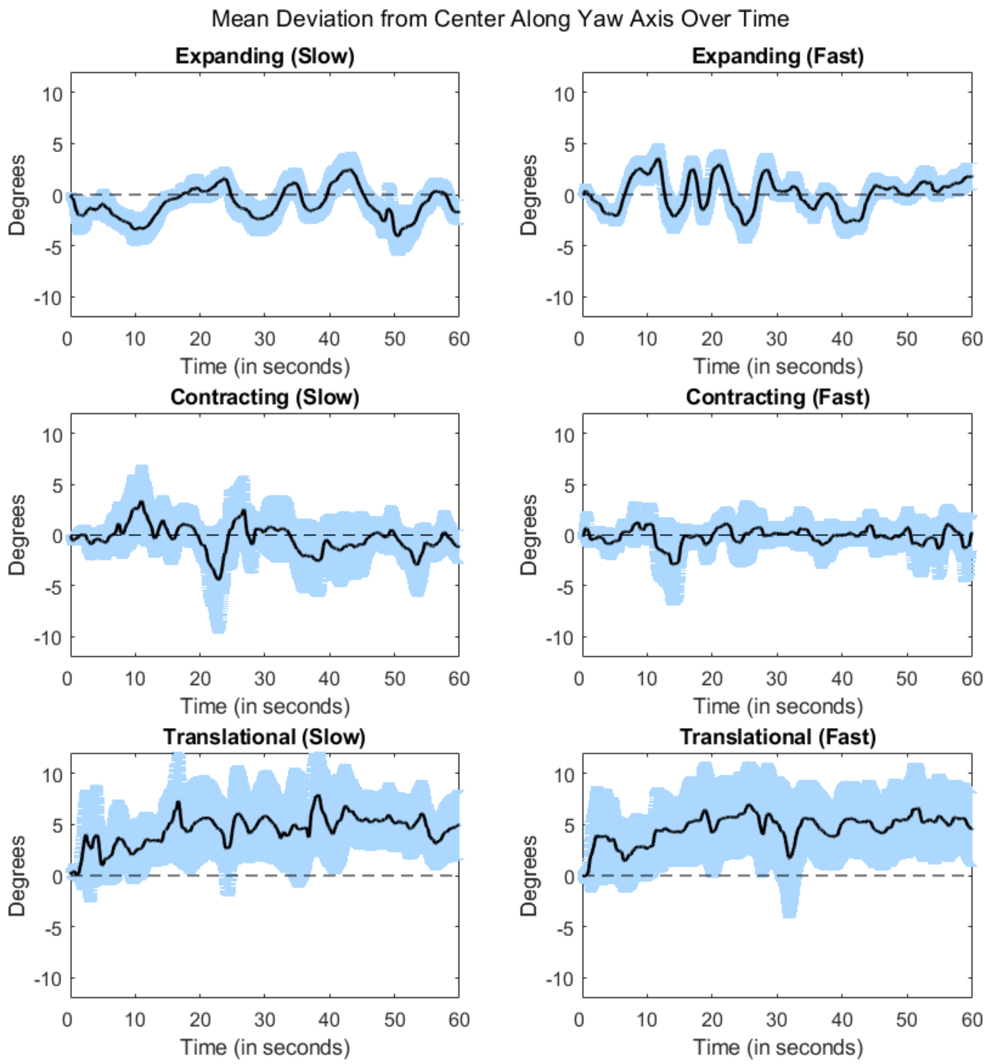

Figure 31. *Plots of mean deviations from center along the yaw axis over time across conditions in Experiment 3. Solid black lines denote the grand mean. Blue bars denote +/- 1 standard error of the mean*

Movement along the yaw axis, however, varied significantly over time – particularly in the expanding motion cue conditions. During the expanding motion cue laps, participants tended to turn their heads left and right along the yaw axis in response to in-simulation turns that take place between the 10-50 second marks (in the slow laps) and the 5-25 seconds (in the fast laps). Note that the behavior of head turning over the course of the entire slow lap is similar to the behavior of head turning over the course of the first 30 seconds of the fast lap. The first half of the fast lap covers the same distance (and same turns) on the virtual track as the entirety of the slow lap because the fast laps are displayed at twice the speed of the slow laps. Furthermore, the error bars (shown in blue in the figures) for the yaw rotations during the expanding laps are noticeably smaller compared to the other motion cue conditions, indicating a greater coherence in head motion behavior across subjects. During the contracting motion cue laps, participants tended to stay closer to center throughout the experiment. During the translational motion cue laps, participants tended to turn their heads slightly left of center, presumably to see the upcoming road more clearly.

To quantify differences in coherence of head motion along the yaw axis across different conditions, we computed the mean and standard deviation of individual participants' correlation to the mean head motion in each condition. The bar graph below (Figure 32) shows the mean correlations across the six experimental conditions. Paired *t*-tests revealed that the correlations in the slow expanding condition ($M = .52$, $SD = .22$) were significantly higher than in the slow contracting ($t = 5.63$, $p < .01$) and slow translational condition ($t = 3.49$, $p < .01$). Similarly, paired *t*-tests revealed that the correlations in the fast expanding condition ($M = .52$, $SD = .24$) were significantly higher than in the fast contracting ($t = 7.47$, $p < .01$) and fast translational condition ($t = 4.13$, $p < .01$).

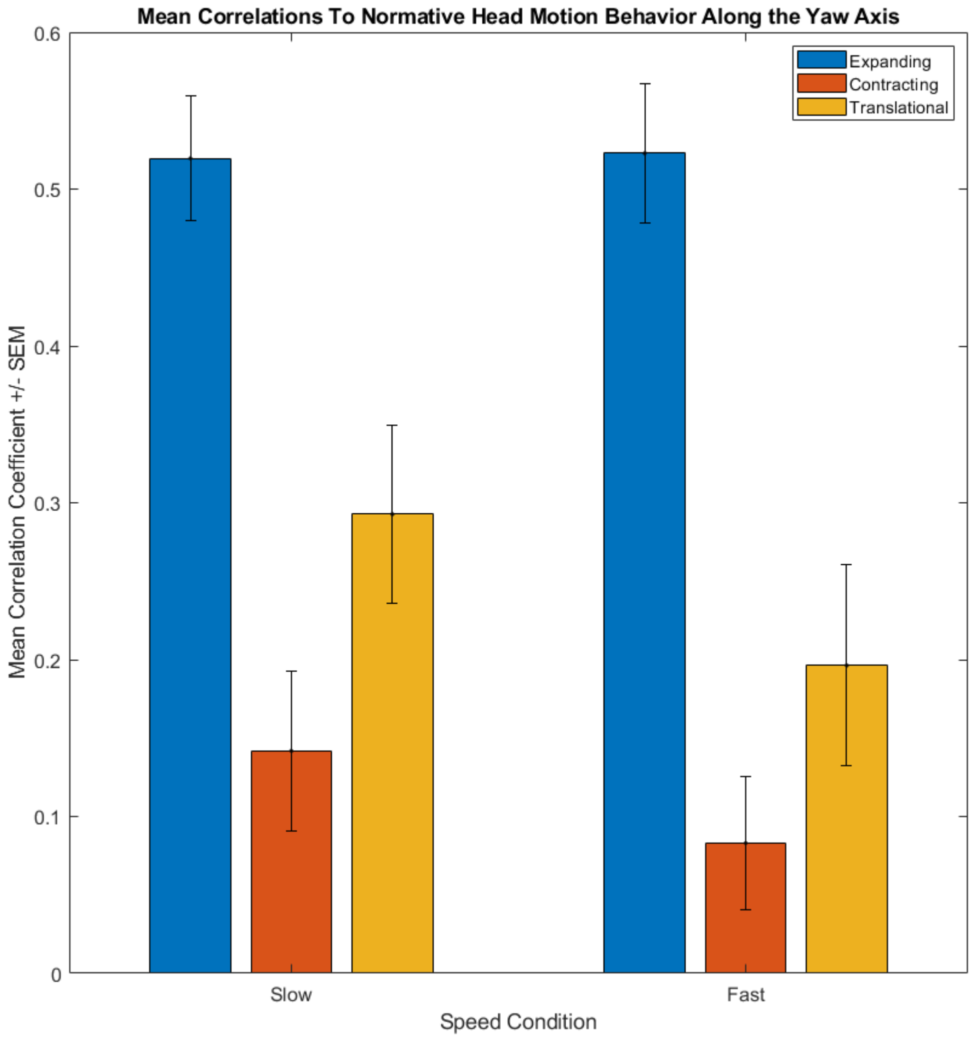

Figure 32. Bar graph showing mean correlations to normative head motion behavior along the yaw axis across conditions in Experiment 3.

Pitch and roll axes were omitted from coherence analyses because deviation along these axes did not vary significantly over time.

Head Rotation as a Predictor of Self-reported Dependent Variables

Head rotation was analyzed in the same way as Experiment 2. To treat head rotation as a predictor of self-reported dependent variables, we examined correlations between average absolute velocity along each axis and self-reported vection, sickness, and presence ratings.

Vection/Absolute Velocity Correlations	Pitch	Yaw	Roll
Expanding (Slow)	-.21 (*p* =.20)	-.17 (*p* = .32)	-.21 (*p* = .20)
Expanding (Fast)	.10 (*p* = .55)	-.02 (*p* = .90)	.03 (*p* = .83)
Contracting (Slow)	-.01 (*p* = .95)	-.07 (*p* = .67)	-.19 (*p* = .25)
Contracting (Fast)	-.13 (*p* = .43)	-.22 (*p* = .17)	-.15 (*p* = .36)
Translational (Slow)	-.09 (*p* = .58)	-.01 (*p* = .94)	-.07 (*p* = .68)
Translational (Fast)	.15 (*p* = .39)	-.02 (*p* = .92)	.09 (*p* = .59)

Table 7. Correlation coefficients between vection ratings and average absolute velocity of head movements across conditions and axes in Experiment 3.

Across all three axes, average absolute velocity of head movements had no significant correlation with vection ratings in any condition (Table 7).

Sickness/Absolute Velocity Correlations	Pitch	Yaw	Roll
Expanding (Slow)	-.06 (*p* =.71)	-.06 (*p* = .71)	-.09 (*p* = .58)
Expanding (Fast)	.06 (*p* = .72)	-.08 (*p* = .62)	.03 (*p* = .88)
Contracting (Slow)	-.08 (*p* = .64)	-.06 (*p* = .71)	-.02 (*p* = .91)
Contracting (Fast)	.00 (*p* = .98)	.07 (*p* = .68)	.01 (*p* = .97)
Translational (Slow)	-.13 (*p* = .44)	-.02 (*p* = .92)	-.14 (*p* = .41)
Translational (Fast)	-.08 (*p* = .64)	-.03 (*p* = .88)	-.10 (*p* = .58)

Table 8. Correlation coefficients between sickness ratings and average absolute velocity of head movements across conditions and axes in Experiment 3.

Across all three axes, average absolute velocity of head movements had no significant correlation with sickness ratings in any condition (Table 8).

Presence/Absolute Velocity Correlations	Pitch	Yaw	Roll
Expanding (Slow)	-0.25 (*p* = 0.13)	-0.08 (*p* = 0.65)	-0.14 (*p* = 0.42)
Expanding (Fast)	0.10 (*p* = 0.54)	0.01 (*p* = 0.94)	0.04 (*p* = 0.80)
Contracting (Slow)	-0.08 (*p* = 0.64)	-0.10 (*p* = 0.56)	-0.23 (*p* = 0.17)
Contracting (Fast)	-0.02 (*p* = 0.91)	-0.07 (*p* = 0.66)	-0.02 (*p* = 0.90)
Translational (Slow)	-0.19 (*p* = 0.26)	0.08 (*p* = 0.65)	-0.14 (*p* = 0.41)
Translational (Fast)	0.13 (*p* = 0.45)	0.07 (*p* = 0.70)	0.06 (*p* = 0.71)

Table 9. Correlation coefficients between presence ratings and average absolute velocity of head movements across conditions and axes in Experiment 3.

Across all three axes, average absolute velocity of head movements had no significant correlation with presence ratings in any condition (Table 9).

We also examined correlations between conformity to normative head motion behavior along each axis and self-reported vection, sickness, and presence ratings.

Vection/Conformity Correlations	Pitch	Yaw	Roll
Expanding (Slow)	0.04 (p = 0.83)	**0.34 (p = 0.04)**	-0.11 (p = 0.52)
Expanding (Fast)	0.09 (p = 0.62)	**0.35 (p = 0.04)**	**0.37 (p = 0.02)**
Contracting (Slow)	-0.11 (p = 0.53)	0.26 (p = 0.13)	-0.05 (p = 0.76)
Contracting (Fast)	-0.23 (p = 0.17)	0.18 (p = 0.29)	-0.12 (p = 0.50)
Translational (Slow)	-0.10 (p = 0.57)	0.01 (p = 0.93)	0.15 (p = 0.39)
Translational (Fast)	0.09 (p = 0.60)	0.01 (p = 0.96)	0.30 (p = 0.07)

Table 10. Correlation coefficients between vection ratings and conformity to the mean head rotation behavior across conditions and axes in Experiment 3. Significant correlations shown in bold.

Conformity to the normative head movement behavior along the yaw axis had a significant positive correlation with vection ratings in the expanding motion cue conditions, at both slow ($r = .34$, $p < .05$) and fast ($r = .35$, $p < .05$) speeds. Conformity to the normative head movement behavior along the roll axis had a significant positive correlation with vection ratings in the expanding condition at fast speeds ($r = .37$, $p < .05$).

Sickness/Conformity Correlations	Pitch	Yaw	Roll
Expanding (Slow)	0.03 (*p* = 0.88)	0.21 (*p* = 0.23)	0.27 (*p* = 0.11)
Expanding (Fast)	-0.13 (*p* = 0.43)	-0.21 (*p* = 0.21)	-0.10 (*p* = 0.55)
Contracting (Slow)	0.05 (*p* = 0.76)	0.06 (*p* = 0.75)	-0.08 (*p* = 0.63)
Contracting (Fast)	-0.02 (*p* = 0.89)	-0.03 (*p* = 0.86)	-0.12 (*p* = 0.49)
Translational (Slow)	-0.04 (*p* = 0.81)	0.08 (*p* = 0.66)	-0.10 (*p* = 0.56)
Translational (Fast)	-0.01 (*p* = 0.95)	0.15 (*p* = 0.37)	0.03 (*p* = 0.87)

Table 11. Correlation coefficients between sickness ratings and conformity to the mean head rotation behavior across conditions and axes in Experiment 3.

Conformity to the normative head movement behavior did not correlate with sickness ratings in any of the conditions or axes.

Presence/Conformity Correlations	Pitch	Yaw	Roll
Expanding (Slow)	-0.02 (*p* = 0.92)	0.24 (*p* = 0.16)	-0.20 (*p* = 0.24)
Expanding (Fast)	-0.08 (*p* = 0.65)	**0.41 (*p* = 0.01)**	0.26 (*p* = 0.13)
Contracting (Slow)	0.02 (*p* = 0.89)	0.32 (*p* = 0.06)	0.01 (*p* = 0.96)
Contracting (Fast)	-0.04 (*p* = 0.81)	**0.37 (*p* = 0.03)**	0.21 (*p* = 0.21)
Translational (Slow)	-0.09 (*p* = 0.61)	0.21 (*p* = 0.21)	0.12 (*p* = 0.50)
Translational (Fast)	0.08 (*p* = 0.65)	0.18 (*p* = 0.28)	0.25 (*p* = 0.14)

Table 12. Correlation coefficients between presence ratings and conformity to the mean head rotation behavior across conditions and axes in Experiment 3. Significant correlations shown in bold.

Conformity to the normative head movement behavior along the yaw axis had a significant positive correlation with presence ratings in the expanding motion cue condition at fast speeds ($r = .41$, $p < .05$) and in the contracting motion cue condition at fast speeds ($r = .37$, $p < .05$).

Just as in Experiment 2, non-conformity to the mean was considered as a possible disqualifying factor for some participants, but ultimately rejected given that the primary analyses returned the same results even with the outlying participants excluded.

Discussion

This experiment replicated the effect of speed on vection magnitude that was discovered in Experiment 2 but failed to replicate the effect of speed on motion sickness and presence. Additionally, this experiment demonstrated that expanding motion cues induce a significantly more compelling sense of vection than contracting and translational cues. This effect could be attributed to a number of underlying mechanisms, including familiarity and realism. The expanding cue condition is the most similar to the average participant's experience with driving in real life (e.g. facing forward, moving forward). While a strong correlation between vection magnitude and presence ratings was observed, expanding and contracting motion cue conditions did not vary significantly in terms of presence ratings. As such, it would be specious to assume that the stronger vection magnitude ratings in the expanding motion cue condition were driven primarily by presence. It is possible that the apparent lack of head movements along the yaw axis in the contracting conditions played a role in comparatively reducing vection, although the mechanism behind this role is currently uncertain.

Limitations

The decision to present the "contracting" laps by reversing the forward-facing laps (rather than by rotating the participant's viewpoint by 180 degrees and presenting the forward-driving lap) was made due to limitations on the available cars within iRacing. None of the available cars had a sufficiently open rear, which would have limited the availability of visual motion cues had the participant been rotated to face out the back of the vehicle. Given the importance of visual cue availability (as established in Experiment 2), we decided to maintain consistency by presenting the forward-facing lap in reverse.

In order to prioritize the effect of visual motion cue direction, we chose to instruct participants to face forward in all conditions. Their head motion was not physically restricted, but their average rotational velocity and average deviation from center was greatly reduced compared to Experiment 2.

In the interest of expediency, this experiment did not include a condition in which participants faced out the *left* window of the vehicle. There is no basis in the literature for a specific difference in left-to-right vs. right-to-left translational motion cues, hence the decision not to include the latter condition. Nevertheless, it is possible that some difference between the two was overlooked.

Chapter V – General Discussion

This dissertation investigated the effects of posture, speed, world alignment, and motion cue direction on vection, motion sickness, and presence. Experiment 1 did not return significant results but provided useful information for the modifications of the follow-up experiments, including information about methodological design, sample size, and stimulus construction. The results of Experiments 2 demonstrated the salience of stimulus velocity (speed) to vection, motion sickness severity, and sense of presence. Higher speeds resulted in a more compelling sense of vection, greater sickness severity, and higher sense of presence. At the outset of the study, world misalignment was expected to result in higher rates of sickness and lower rates of presence, but that prediction was not demonstrated by the results. Instead, visual cue availability proved to be a more salient influence on vection. This suggests that lower order visual aspects of the stimulus may have a greater effect on vection than higher order effects. Experiment 3, however, did not demonstrate an effect of speed on sickness, even in the expanding cue condition (which is most similar to the upright, world-aligned condition in Experiment 2). This inconsistency could be attributed to a lower sample size or perhaps to the fact that fewer laps were presented in Experiment 3.

One of the initial goals of this series of experiments was to identify factors that maximize vection and presence while minimizing sickness. Towards this goal, Experiment 2 has identified that stimulus velocity (speed) is a key factor in vection, sickness, and presence. Overall, presence ratings in Experiments 2 and 3 did not correlate with sickness ratings. This suggests that, within the current methodological framework, one's higher order sense of presence is largely unrelated to one's likelihood to experience sickness (which is likely driven by lower order factors such as stimulus velocity). This runs contrary to the review by Weech et al. (2019) which concluded that presence and cybersickness are generally negatively related. Another notable finding was the strong and consistent correlation between vection magnitude and presence ratings in both Experiments 2 and 3. This suggests that one's ability to experience illusory self-motion is tied to one's sense of presence in the virtual environment, which is consistent with recent work by Kooijman et al. (2022).

Another goal was to determine whether reclined posture would affect multisensory processing in such a way that sickness would be reduced. The initial assumption was that lying down might downweigh vestibular cues, thus mitigating the conflict between moving visual cues and stationary vestibular input. However, posture did not seem to directly contribute to motion sickness severity. This suggests that vection and sickness can occur regardless of one's seating position. Assuming that VR-induced motion sickness is driven by sensory conflict, this finding could mean one of several things. It could mean that postural changes do not trigger sensory re-weighting in such a way that mitigates sensory conflict. It could also mean that the postural manipulations present in this study were not extreme enough to trigger a meaningful re-weighting of vestibular cues. Alternatively, it could mean that the positive presence of visual cues has a much greater influence in the sensory conflict mechanism than the negative presence of vestibular cues.

When collapsed across conditions, vection magnitude and motion sickness severity had no significant correlation. This finding aligns with a larger body of work that suggests a complex relationship between vection and motion sickness (Keshavarz et al., 2015; Palmisano et al. 2017). Existing literature has suggested that, although there is some evidence to suggest a positive correlation between the two (Moss & Muth, 2011; Palmisano et al. 2007), other studies have failed to find correlations (Riecke et al. 2015), while others have demonstrated negative correlations (Bonato et al. 2008). Further research into the specific scenarios in which the two phenomena influence each other is warranted.

The thorough analyses of head rotation data in Experiments 2 and 3 resulted in several notable findings. First, it was established that head movement along the yaw axis follows a very consistent pattern among participants in the expanding cue conditions. Participants reliably turn their heads in response to in-game movements, even when instructed to stay relatively still. This demonstrates that immersive virtual reality driving simulations have the potential to prompt realistic behavioral responses, even in the absence of vestibular cues. Second, head movement velocity appears to have a complicated relationship with the subjective experiences of self-motion and presence, but not motion sickness. This was relatively surprising, given that interactions between visual and vestibular information form the basis for sensory conflict theory. Voluntary and involuntary head motions could prove to be a useful metric for understanding self-motion experiences in follow-up studies.

General Limitations

The experiments discussed in this dissertation suffered from a number of limitations due to software and hardware restrictions. Most notably, the driving simulation software could not adjust the angle of viewing beyond 30 degrees along the pitch axis. As such, this limited the options for postural and visual manipulations in all three studies. Furthermore, the software did not include a vehicle with an open rear, which introduced a limitation in the contracting-cue condition of Experiment 3. Without this limitation, contracting motion cues could have been explored in a more naturalistic manner (e.g. looking out the back of the car as it moves forward rather than looking out the front of the car as it reverses).

One general limitation was the fidelity and resolution of the simulation. A high-fidelity stereoscopic recording of a lap around the real-life track would have been preferable to a 3D render of the same track, but such a recording was not available. More powerful hardware (e.g. better GPU, higher resolution head-mounted display) would have allowed for a more detailed rendering of the stimuli, which could have perhaps yielded a stronger sense of presence/immersion in the participants.

Another salient factor that was excluded from the studies was the ability for participants to exert some form of control over their own movement. These factors were excluded in order to make sure that the visual stimuli were consistent across participants. The desire to control and standardize the motion stimuli informed the decision to exclude these factors, but perhaps a more comprehensive study could examine the relative salience of user control, particularly for the measures of sickness and presence.

Finally, the current studies lacked vestibular cueing, which limits the assumptions that can be made regarding sensory conflict theory and also limits the degree to which the results can be generalized to real-world driving conditions. Additionally, the claims that can be made regarding the impact of postural stability are limited because these experiments did not include a condition in which participants were standing. Instead, all conditions (seated and reclined) were relatively stable in terms of posture.

Future Studies

Future studies could build upon these findings by introducing more extreme manipulations of posture, speed, and user control. Assuming that the aforementioned limitations in software/hardware can be overcome, future studies could examine whether a fully reclined (e.g., lying all the way down, facing upwards towards the ceiling) posture would have a noticeable effect on vection, sickness, and/or presence. Existing literature suggests that fully reclined posture can affect one's reliance on visual/vestibular cues (Ward et al., 2017), which could have implications for one's sense of both vection magnitude and sickness (especially if sickness is driven by apparent conflict between available visual and vestibular cues).

Follow-up studies could also utilize more fine-tuned manipulations of speed. Specifically, such a study could determine whether there are upper and lower limits for the effect of speed on vection and sickness. Such a study could determine whether the relationship between speed, vection magnitude, and sickness is linear, or if the impact of speed levels out at a high enough (or low enough) velocity. Future studies could also focus on the impact of acceleration/deceleration on vection and motion sickness. Given that the vestibular system is particularly sensitive to changes in speed (rather than detection of constant speed), it would follow that sensory conflict and sickness would occur most noticeably during acceleration/deceleration. While the current experiments only included acceleration up to top speed within the first 5-15 seconds of the laps, follow-up experiments could employ a simulation that speeds up and slows down at various points in time. Combined with head rotation data, such a follow-up study could potentially reveal new, quantifiable behavioral reactions to changes in speed, as well as subjective assessments of relevant dependent variables.

Subsequent experiments could also address one of the primary limitations of the present studies by introducing real vestibular cues. Such cues could be provided by a haptic/motion device/platform that moves in accordance with the stimuli. Using such a device would allow for a more realistic presentation of the stimuli, as well as allowing for the manipulation of vestibular cues. Additionally, this type of manipulation would carry more directly applicable findings for real-world applications of both conventional and autonomous driving.

The current experiments represent a first step towards understanding the complex relationship between vection, cybersickness, and presence in naturalistic, ecologically valid contexts. Furthermore, this dissertation has outlined a thorough and coherent methodological framework for examining and quantifying head movements in during virtual reality simulations. These methods can serve as a foundation for future research in a variety of contexts, both virtual and real. It is important to continue investigating interactions between subjective experiences and quantifiable behavioral responses, in the hopes that a more holistic understanding will pave the way for improved accessibility of virtual reality applications and hardware.

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