Self-motion illusions ("vection") in Virtual Environments: Do active control and user-generated motion cueing enhance visually induced vection?

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Abstract

The human perceptual system can be tricked into believing that one is moving, when in fact, one is not. These self-motion illusions (vection) can be exploited to convincingly simulate self-motion without the need for costly and cumbersome motion platforms. Traditionally, vection has been elicited by moving visual stimuli on custom optokinetic drums or virtual reality (VR) setups. Surprisingly, little is known about contributions of cross-modal effects on vection in contemporary, interactive VR applications. Two studies investigated the effect of active versus passive locomotion and small, actively versus passively generated physical motion cues on optic flow based vection. Twenty four participants used a joystick or gaming chair to navigate on curved (experiment 1, training) or a combination of curved and straight trajectories (experiment 2, main study) presented in an immersive, 3D VR system. The gaming chair allowed for 10 centimeter forward/backward and left/right swivel motions of the seat. Participants experienced four conditions: 1) just watching the scene (passive, no motion cueing), 2) motion cues applied to the participant's seat (passive, motion cueing), 3) joystick locomotion (active, no motion cueing) and 4) participants using the gaming chair for locomotion (active, motion cueing). Overall, participants took 16% longer to experience vection for active compared to passive locomotion. Small, physical motion cues increased vection intensity by 22%. Trajectory curvature most consistently affected vection. Participants experienced vection 34% more intense, 20% earlier and 9% more likely during narrow turns compared to straight paths. Participants experienced vection up to 18% earlier in experiment 2 over experiment 1 possibly due to training effects. It seems that actively controlling locomotion may have distracted participants from the motion stimulus or the task of reporting vection. It became evident that smoothness, precision and ease-of-use of the interface were possible factors that affected vection. In conclusion, vection can be enhanced by using simple motion paradigms and adding curved trajectories to the simulation at minimal cost and effort. For interactive applications, prudent selection of interaction paradigms and ample training is advised.

Keywords: vection, self motion illusions, motion cueing, self-motion simulation, human factors, psychophysics, virtual reality, cue integration, active/passive interaction

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List of Acronyms

FOV	Field Of View
HRTF	Head Related Transfer Form
HMD	Head Mounted Display
Hz	Hertz
VE	Virtual Environment
VR	Virtual Reality

1. Introduction

Self-motion and the experience thereof is a crucial component of our daily lives that help us to successfully interact with our environment. Self-motion is essential to human and most animal survival; without it food, a suitable partner and social connections are hard to come by. When we move about through space, salient and coherent motion information is provided to us through various sensory modalities in the form of visual, vestibular, auditory, somatosensory and biomechanical cues as well as internal afferent/re-afferent motor commands. Each of our senses captures a physical dimension of our body interacting with its environment while moving. Despite the tremendous amount of information, our brain quickly, effectively and effortlessly detects self- and object motion when we naturally move about. Under most natural circumstances, this perceptual system is quite accurate and robust. However, there are situations under which this complex yet effective system fails to convey the truth so that we are “tricked” into believing something that is not really there.

As an example of these illusions, let us look at a scenario that one encounters in traffic from time to time: We are located in a car waiting in a lineup in front of an intersection. On the adjacent lane there is a large truck and trailer or recreational vehicle waiting for its turn as well. We pay attention to this vehicle as it moves ahead. Almost instantaneous to the motion of the adjacent vehicle, the illusion begins to appear. Instead of the other vehicle, we perceive ourselves in motion despite the fact that we are still physically stationary and waiting in line. Strangely, we don’t experience moving forward but backward so that we instinctively apply pressure to the brakes to avoid colliding with the vehicle behind us. For those who use the train frequently, this illusion of self-motion can be observed as well by looking at an adjacent train pulling out of the station while one is waiting (Helmholtz, 1867).

In some cases, these illusions of self-motion can be very convincing, exhilarating and almost indistinguishable from actual self-motion, despite the knowledge that one

does not physically move. This property has attracted researchers and engineers alike to investigate this phenomenon for various purposes. Over the past 130 years, efforts have been undertaken to replicate circumstances under which we perceive these illusions. For example, Amariah Lake created a unique amusement park ride presented at the San Francisco Midwinter Fair in 1895 and called it the “Haunted Swing”. For the event, he built a fully furnished tumbling room with a swing mounted at its center. While the swing remained stationary for the most part (except for slight vibrations applied to the swing itself), the room tumbled around the observer. The tumbling action induced a distinct impression that one was actually swinging through the room. Wood (1895) described his experience within the “Haunted Swing” as “empty” and experienced sensations of “goneness within” as if riding an elevator, a feeling of “leaning forward” and an involuntary response to perceived backswings in the form of postural adjustments, such as clutching at the seat to avoid sliding off the swing. Wood observed that other participants experienced dizziness, nausea and even fainting during and after the ride as if they actually experienced an actual swing.

1.1. Motivation

Today, visitors still want exhilarating motion illusions and they can now be experienced in most theme parks or 3D/IMAX theaters. Practically, self-motion illusions may help to improve the user experience within artificial environments such as 3D/IMAX theaters, 3D games, theme park rides or virtual reality applications where technology is used to place participants into a mediated or virtual environment for a specific purpose. Especially for virtual reality (VR), the goal is to “…re-create the actual experience, combining vision, sound, touch and feelings of motion engineered to give the brain a realistic set of sensations” (Atkins, 2008).

Besides exhilarating self-motion experiences, participants may get less confused and disoriented in these artificially spaces when experiencing self-motion illusions compared to conditions where they do not. For example, when participants remember the layout of their surrounds, close their eyes and physically rotate in place and are then asked to point to any object in the room with eyes still closed, they can do so quickly and accurately as they seem to have updated the spatial relationship between them and the

objects during the self-rotation. However, when participants are asked to once again close their eyes, but merely imagine their new heading instead of actually rotating there, they have difficulty to update the spatial relationship between them and their surround so that when asked to point to any object in their surrounds, their responses take more time and are more error prone compared to conditions of physical rotations (Rieser, 1989). Somehow, actual self-motion enables us to automatically, quickly and accurately update relationships between ourselves and our surrounds whereas merely imagining self-motion does not. Actual, physical self-motion has thus been believed to be a prerequisite for reflex-like spatial updating, something that is frequently missing in, gaming and VR applications.

To investigate whether actual self-motion is really necessary for spatial updating, Riecke and von der Heyde proposed the idea that self-motion illusions may be sufficient to trigger these automatic spatial updating processes (Riecke & von der Heyde, 2002). Riecke later found evidence that participants point more accurately to objects in their surrounds and have a better knowledge of where objects are relative to themselves in conditions of illusory rotations compared to imagined rotations (Riecke, Feuereissen, Rieser, & McNamara, 2012).

Self-motion illusions may then impact applications where convincing and natural sensations of self-motion can be useful such as, for example, vehicle operator training where participants are being prepared for situations they may encounter when flying an airplane or driving a vehicle.

In motion and operator training simulators in particular, self-motion sensations have traditionally been generated using actual, physical motion cues. Forces are applied to the platform or cabin where participants are located and are somewhat concurrent to other information about self-motion such as visual cues. Participants are then either passively exposed to the scenario or actively control the system and locomotion based on the control paradigms of the simulation. The use of these motion platforms can be very complex and require expertise and effort to set up, run and maintain. But despite the effort, they frequently fail to produce the intended outcome. For example, participants often notice a lack of convincingness and realism (Riecke, 2011, Riecke & Schulte-Pelkum, 2006; Hettinger, 2002); in severe cases, they report occurrences of

dizziness, disorientation or symptoms of motion sickness (Harm, 1990; Lawson, Graeber, Mead, & Muth, 2002).

There are some explanations as to why these effects may occur during self-motion simulations. For example, we attempt to simulate physically correct motion cues, but technical limitations often prevent us from doing so. Actuators, the weight/sensitivity of the equipment being moved and mechanical linkages between actuators and platform limit its motion such as acceleration force, velocity and range of motion. Trial-and-error procedures are commonplace to calibrate or “tune” the system until it approximates the desired outcome. This mere approximation coupled with possible dissonances between visual and vestibular cues are a possible cause of discomfort and motion sickness (Reason & Brandt, 1975).

Our understanding of self-motion illusions may be leveraged to convincingly simulate self-motion while relaxing requirements of physical self-motion simulations towards perceptually effective instead of physically correct self-motion simulations (Riecke & Schulte-Pelkum, 2006). Lawson and colleagues suggest that “A solution might be finessed by exploiting known principles of sensory functioning…” [p. 141] in situations where experiences of self-motion are desirable, but without obvious solutions or great difficulty (Lawson, Sides, & Hickinbotham, 2002).

The understanding of how we perceive self-motion may not only positively affect how we design and use VR systems in the future, but help us build theories and frameworks towards a better understanding of how our brain works. For example, despite the fact that our perceptual system has evolved relying on various types of motion cues in conjunction, it seems that sensory modalities can be disambiguated in the context of self-motion perception as seen in previous examples of self-motion illusions where vision alone was sufficient to induce a compelling sense of self-motion.

The phenomenon of self-motion illusion can be a highly useful tool for systematically investigating self-motion perception, especially in conjunction with VR technology. Self-motion illusions allow us to disambiguate senses to study and dissect each modality in isolation towards the formulation of hypotheses and the definition of motion parameters and their relationship to resulting self-motion percepts. This

disambiguation of senses may help us to selectively combine sensory modalities to study their interaction and behavior under highly controllable conditions.

To further understand the experiential phenomena of self-motion, we ask ourselves the following question: How does our brain perform the complex task of self-motion perception? To date, we still need to dive further into the perceptual system to fully explain its mechanisms and predict its behavior, both on a neuronal as well as a cognitive level. For example, we understand how sensory receptors physically operate, but we do not fully know the function between parameters of a motion stimulus and the resulting self-motion percept nor have we identified all parameters for each sensory modality relevant for self-motion perception. Much is still unknown about the processes that integrate motion cues across sensory modalities into a robust self-motion percept (sensory fusion) and how we cognitively process or interpret this information on a higher level in relationship to factors such as, for example, knowledge, expectations and emotional states.

Our goal of this thesis is to investigate relationships between motion parameters and resulting self-motion illusion percepts in a series of experiments. The following subsections introduce relevant background information about terms and properties related to visually induced self-motion illusions as well as methods to trigger this experiential phenomenon. After a brief review on each topic, a short paragraph elaborates why and how this information was applied in the context of this thesis and our research questions (see subsection 1.3).

1.2. Self-motion illusions (“Vection”)

Vection stands for self-motion illusion and is a term coined by Fischer & Kornmüller (1930) and Tschermak (1931) that describes an experiential phenomena where convincing, embodied self-motion is experienced without actually (physically) moving. One of the earliest reports date back to 1867 when it was first mentioned during the early days of railway transit (Helmholtz, 1867). In the century of vection research since (see Mach (1875)), most of the research has been centered around vision (Dichgans & Brandt, 1978; Hettinger, 2002).

Traditionally, vection has been elicited in stationary observers using optokinetic drums (Brandt, Dichgans, & Koenig, 1973; Dichgans & Brandt, 1978). An optokinetic drum is a mechanical device that produces a visual motion stimulus and its main component is a cylinder that usually bears vertical stripes on the inside. The cylinder is suspended, much like a shower curtain and a participant is seated in the center of the cylinder staring or fixating at a point on the cylinder wall. The cylinder is then spun up and presents a repetitive motion pattern to the observer. Initially, the participant "correctly" perceives the cylinder, or background as rotating (background motion). Depending on the motion stimulus, modality and various other factors, after 2-30 seconds the observer begins to perceive self-motion in the opposite direction of the motion stimulus relative to the rotating cylinder (Berthoz & Droulez, 1982; Dichgans & Brandt, 1978). This phenomenon gradually sets in where the background motion (the cylinder) becomes stationary and the observer experiences turning in place. Once the participant perceives the background as stationary and is thus "convinced" he is moving, vection has reached full saturation.

In the case of the optokinetic drum mentioned above, participants experienced turning in place around the earth vertical axis. Besides turning, straight path or linear self-motion illusions are similarly elicited using linear motion patterns (Howard, 1982). Two approaches have been used to elicit visually induced linear vection: Traditionally, the observer's head was placed between two projection screens or monitors that were located on either side and adjusted so that the displays optimally covered a large part of the peripheral view. Linear motion patters then elicited a convincing sense of translation (Berthoz, Pavard, & Young, 1975; Lepecq, Jouen, & Dubon, 1993). Alternatively, a centrally located display can be used in conjunction with expanding or contracting motion patterns (Andersen & Braunstein, 1985; Palmisano, 1996). The combination of both, circular and linear motion patterns produce vection along a curvilinear trajectory, much like travelling on a meandering street. Vection, regardless of trajectory or whether it is turning in place, requires time (or vection latency) from the start of the motion stimulus to the full saturation of vection where the participant experiences exclusive self-motion and consequently no background motion (Berthoz & Droulez, 1982).

Vection is a result of motion information within the presented stimulus. The information about self-motion is extracted based on optic transformations, or optic flow

(Gibson, 1979) of the image on the retina. The relative motion between observer and environment visually results in an apparent motion of objects. The pattern of this apparent motion is known as optic flow and its structure is determined by surfaces, edges (for example the vertical stripes in an optokinetic drum) and objects that pass by the observer over time. Optic flow contains information about heading, velocity and travelled distances. For example, even when navigating through a deprived environment such as a simple star field or dot-cloud, we commonly do have access to the aforementioned features of self-motion (Bremmer & Lappe, 1999; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). The magnitude of changes in optic flow patterns over time indicate the magnitude of self-motion. In the context of vection, increasing frequency of visual patterns increase the magnitude of perceived vection (Brandt et al., 1973). The potential of optic flow to induce vection thus depends on visual parameters that determine the structure of the optic flow field.

Creating motion stimuli by defining and controlling parameters of optic flow allows a great deal of control over the motion stimulus. We thus generated a suitable optic flow field to induce visual vection in our series of experiments. Optic flow has traditionally been generated in the form of patterns animated by mechanical devices, but in the context of this thesis, VR technology was used to computer-generate these animated patterns of motion. VR technology offers a greater degree of flexibility as the optic flow patterns can be parameterized and do not rely on physical implementations of patterns (such as vertical bars on canvas). VR technology today is a common approach to generate optic flow fields or even naturalistic motion stimuli.

1.2.1. Circular and linear vection

While visual vection around the vertical or yaw axis has been the most frequently investigated case of vection (Dichgans & Brandt, 1978), it has been known to occur along and around all body axes, much like their real-world counterparts. Thus, vection can be experienced as linear forward/backward translation along the x axis, as leftward/rightward translation along the y axis and as upward/downward translation along the z axis. Likewise, vection can be experienced as circular counterclockwise/clockwise rotation around the x axis (roll), as upwards/downwards rotation around the y axis (pitch) and as left/right rotation around the z axis (yaw). The

terminology for vection is categorized based on two classes of self-motion experienced: circular vection for roll, pitch and yaw illusions and linear vection for illusions of translations along the x, y and z axes (Fischer & Kornmüller, 1930; Tschermak, 1931).

Though vection can be elicited along and around all body axes, the ease to induce vection and its compellingness is believed to depend on whether or not the direction of the gravitoinertial vector is changed. For example, linear up/down vection is more compelling and is perceived earlier than their forward/backward or left/right counterpart (Giannopulu & Lepecq, 1998). Likewise, circular vection around the earth vertical axis (yaw) can be elicited more easily compared to roll or pitch circular vection (Trutoiu, Mohler, Schulte-Pelkum, & Bülthoff, 2009). It is believed that circular and a combination of circular and linear (curvilinear) vection are similarly convincing and easy to elicit. Both, circular and curvilinear vection are more convincing to linear vection (Trutoiu et al., 2009). In their study, Trutoiu and colleagues concluded that the number of circular or curvilinear trajectories should be maximized to increase the sense of self-motion.

Combinations of straight paths and curvilinear trajectories are quite common when navigating through our environment. Since turning in place has been extensively studied and found to be experientially similar to curvilinear trajectories in the context of vection (Trutoiu et al., 2009), we opted for linear and curvilinear vection in our experiments.

1.2.2. Vection metrics

If we could objectively measure vection, we would draw direct comparisons and conclusions across studies, modalities and the entire field of vection. However, because vection is a subjective experience, no objective measures are available to date and an indirect process of assessment is necessary. Commonly, a combination of measures is used to assess vection occurrence, latency, degree (i.e. force, strength, compellingness, realism, velocity or distance travelled) and direction (i.e. left/right, forward/backward or up/down) (Diener, Wist, Dichgans, & Brandt, 1976; Ohmi & Howard, 1988).

Magnitude estimations (Stevens, 1957) in form of introspective self-reports are commonplace. Participants either verbally or through some sort of action (i.e. button-

press) indicate when they experience vection, to what degree and in what direction they feel they are moving. Another approach is to gauge behavior that participants exhibit during vection where experimenters estimate the magnitude of perceived self-motion based on visible tell-tale signs such as postural adjustments or nystagmoid eye movements. It is believed that the quality of the perceived self-motion in participants is directly linked to the amount of their postural adjustment, stability or other visible behavioral signs (Agaeva & Altman, 2005; Dichgans & Brandt, 1978; Kapteyn & Bles, 1977; Marmekarelse & Bles, 1977). Dietrich and colleagues for example, looked at nystagmoid eye movements that are usually observable after spinning observers in place (Dieterich, Bense, Stephan, Yousry, & Brandt, 2003). They suggested that participants who experienced strong, visually induced self-motion will exhibit an afternystagmus within a few seconds after the motion inducing stimulus had been removed.

For both, self-reports and behavioral observations, vection data is measured through estimations that rely on the ability of the participant or experimenter to reliably and accurately gauge the magnitude of vection. As a result, human error can unsystematically affected vection data. In the case of behavioral observations, researchers face additional challenges to accurately measure behavioral changes to venture beyond informal observation. Firstly they need to know what exactly they measure and if the chosen measure (i.e. leaning forward) maps well to the perceived self-motion sensation. Secondly, methods have to be put in place to precisely measure the amount of behavioral change for all observers in the same manner. In practice, it is commonly found that these methods require complex setups such as calibrated body-mounted accelerometers, video capturing techniques or mechanical devices like force platforms.

An obvious solution to the challenges of magnitude estimations are direct, physiological measures and various techniques are currently being investigated; in particular electrodermal activity, cardiovascular responses (Cheung, Hofer, Heskin, & Smith, 2004) and neurological activity. The latter has been receiving some attention lately and various brain activity assessment techniques are being investigated in the context of vection such as electroencephalography (EEG) (Stern, Koch, Stewart, & Vasey, 1987), positron emission tomography (PET) and functional magnetic resonance

imaging (fMRI) (Baumgartner, Valko, Esslen, & Jäncke, 2006; Brandt, Bartenstein, Janek, & Dieterich, 1998; Tokumaru, Kaida, Ashida, Yoneda, & Tatsuno, 1999).

Although physiological measures could possibly reduce the influence of human errors on measuring vection, they don't seem to be commonly used in vection research and much work is still needed to establish reliable metrics that accurately represent the occurrence, quality and quantity of vection. Despite the drawbacks associated with estimations of magnitude, these psychophysical measures have shown a high degree of psychometric reliability (Kennedy, Hettinger, Harm, Ordy, & Dunlap, 1996) and have thus been adopted, widely accepted and put to practical use throughout the vection research community (Wright, DiZio, & Lackner, 2006).

Despite best assessment practices, researchers commonly find that vection experiences vary greatly from person to person under identical stimulus conditions. Kennedy and colleagues investigated whether vection exhibits monotonic, reliable and stable psychometric differences (R. S. Kennedy et al., 1996). They noticed that intra-participant variability is low, but that inter-participant variability is typically high, particularly for vection latency and intensity metrics. It is believed that these inter-personal differences may occur because of cross-modal interaction, that is, other sensory information that can either facilitate or inhibit vection. A common conflict in situations of vection occurs between the vection inducing stimulus and vestibular information that indicates no-motion as one is merely being "tricked" into experiencing self-motion instead of actually, physically moving. Because the health and degree of functionality of the vestibular systems varies from person to person, vestibular conflict cues may vary as well and as a result, the vection experience functionally depends on individual vestibular sensitivity (Lepecq, Giannopulu, Mertz, & Baudonniere, 1999).

For the scope of this thesis, we chose to stay within established measures and techniques and thus relied on self-reported magnitude estimates of well-trained participants, specifically vection occurrence, intensity of the self-motion experience and latency. We furthermore limited a possible source of inter-participant response variability by excluding participants with dysfunctional vestibular systems from our study.

1.2.3. Visually elicited vection

In the context of self-motion illusions, the visual and vestibular contribution to self-motion perception are quite well studied and understood (Dichgans & Brandt, 1978; Warren & Wertheim, 1990), possibly because these two senses are believed to be instrumental for perceptions of self-motion (Howard, 1986a, 1986b; Warren & Wertheim, 1990) and are also most frequently leveraged in VR, gaming, theater or theme park applications. The following review thus focuses on factors that affect visually induced vection relevant in the context of our study.

1.2.3.1. The visual field

The extent to which the motion stimulus covers the visual field greatly affects vection, an idea that seems intuitive given that natural self-motion affects our entire field of view. Large visual changes are more likely caused by self rather than object motion. Berthoz et al. (1975); Brandt et al. (1973) and Dichgans & Brandt (1978) found that increasing FOVs correlate with increased vection responses up to the point where the perceived self-motion becomes indistinguishable from the physical self-motion counterpart for full-field visual simulations. Brandt et al. (1973) found that vection latency and intensity changed as a function of FOV where vection latency declined and vection intensity increased with greater FOVs.

For example, Sato, Seno, Kanaya, & Fukazawa (2007) increased the field of view of their motion stimulus presentation by adding a floor projection system that depicted a moving floor plane and found that linear vection was facilitated using this approach. Trutoiu et al. (2009) confirmed that both, circular and linear vection are facilitated by panoramic displays. They found that illusions of linear translations in particular benefit from curved panoramic screens. The former is in line with typical linear vection approaches where displays depicting the linear motion stimulus are placed parallel to the viewers head covering most of the periphery.

Even though large FOVs are predominantly used to elicit visual vection, a centrally located motion stimulus within small FOVs can be sufficient especially in situations when large FOVs are unfeasible. For example, Berthoz et al. (1975), Brandt et al. (1973) and Dichgans & Brandt (1978) found that small FOVs can elicit vection under

carefully implemented laboratory conditions. When the motion stimulus is optimized so that the FOV effect is enhanced, Andersen & Braunstein (1985) for example, showed that centrally located radially expanding motion patterns coherent with linear self-motion in the forward direction can elicit linear vection using small FOVs. It is thus possible to elicit vection under small FOV conditions as long as motion stimuli are carefully considered and conflicting cues properly controlled for.

The goal of our experiment setup was to keep the implementation within the scope of commercially available hardware for easy replication in the context of home gaming and VR. We produced large FOV visual motion information that could be replicated using traditional front projection setups or consumer grade 3D televisions. We thus forewent complex curved or multi-projector systems in an attempt to make our findings more applicable to practice. However, we maximized the vection inducing effectiveness of traditional, planar display surfaces by adding stereoscopic viewing (see 1.2.3.3) and dynamic viewpoint adjustment (see 1.2.3.4). Instead of using floor projection, we provided additional, lamellar flow parallel to direction of movement through a textured floor plane as part of an optic flow field which we used to visually elicit vection (see subsection 2.2).

1.2.3.2. Visual velocity, spatial frequency and fixation patterns

Stimulus velocity, spatial frequency and eye fixations are believed to directly affect vection velocity. For example, Brandt et al. (1973) as well as Howard (1986a) found that stimulus velocity is directly proportional to the perceived velocity, but increasing stimulus velocity beyond a certain limit gradually reduces its effectiveness and is eventually perceived as moving (thus changing back from self-motion to background motion). The threshold values reported differ slightly from study to study. Howard (1986a) for example, suggested a threshold of approximately 90°/s whereas Brandt et al. (1973) identified a value of 120°/s for circular vection. Increasing turn velocities can result in higher vection convincingness and intensity ratings and lower vection latency responses (Riecke, Schulte-Pelkum, Avraamides, Heyde, & Bülthoff, 2006; Riecke, 2006; Schulte-Pelkum, Riecke, von der Heyde, & Bülthoff, 2003).

The perceived velocity of the visual stimulus is not solely determined by its physical velocity, but also by the structure of the stimulus. For example, Diener et al.

(1976) found that higher spatial content such as edge rate or contrasts (scene detail or black/white vertical bars) in the motion stimulus correlate with greater perceived vection velocities. These findings are indirectly corroborated by Dichgans & Brandt (1978) and Brandt, Wist, & Dichgans (1975) who found that high-density environments can increase vection convincingness.

The effects of stimulus velocity and spatial frequency may be modulated depending the central focus of the eyes. An early mentioning of this effect can be found in (Mach, 1875) who improved the sensation of vection in participants by having them fixate on a stationary object in front of the moving stimulus. His findings were later confirmed by Fushiki, Takata, & Watanabe (2000) as well as Becker, Raab, & Jürgens (2002), for example. In the case of Becker et al. (2002), participants were instructed to either smoothly follow the stimulus with their eyes or to keep them fixated on a foreground object. Participants reported higher vection latencies and lower perceived vection velocity (thus reduced vection) for the condition during which they smoothly followed the motion patterns with their eyes. This effect can be explained by a reduction of perceived velocity when the eye is following the motion stimulus versus an increase in perceived velocity for fixated eyes. Thus, disambiguation of stimulus velocity, spatial content and eye movements need to taken under consideration to explain perceived self-motion velocity.

It is important to note that stimulus velocity, spatial frequency, fixation patterns and display technology are connected in the context of image perception. High stimulus velocities, spatial frequency and rapid eye motions can produce a perception of image blurring, flicker or color separation. With the increasing popularity of VR technology and the common 60 Hz refresh rate limits of contemporary display technology, stimulus velocities above 60°/s can be challenging to implement without these visual artifacts. For more information about display technology in context of visual perception, please refer to a more in-depth review on the matter (Riecke, Nusseck, & Schulte-Pelkum, 2006).

In the context of our investigations, we controlled stimulus velocity by using an identical optic flow field and linear velocity during all experiment conditions. Trajectory variables were identical linear velocity for all conditions and variable turn velocity. In conjunction with and depending on the turn velocity, the result was either a linear or a

curvilinear trajectory with varying degrees of curvature. We chose turn velocities well below 60 º/s to avoid shortcomings of the display technology we used and to maintain a reasonably comfortable viewing condition for our participants. To reduce effects of eye motions on perceived velocity during the experiments, participants were instructed to focus on an object on the screen; please refer to Figure 2-6 for more detail.

1.2.3.3. Stereoscopic information

There is evidence that binocular disparity affect perceptions of vection. For example, Palmisano (1996, 2002) used an optic flow field that contained randomly distributed squares to elicit linear forward vection. They compared conditions of monocular and stereoscopic viewing and found that consistent stereoscopic depth cues facilitated vection, particularly perceived velocity and distance travelled. Vection velocities were experienced closer to the stimulus velocity (higher reported velocity) and thus participants perceived longer distances travelled under stereoscopic viewing conditions. Lowther & Ware (1996) investigated linear and circular vection based on optic flow and found a similarly beneficial effect of stereoscopic cues particularly on vection latency. The positive effect of stereoscopic cues on vection can be explained by additional self-motion cues available to the visual system in form of exponentially increasing object disparity as objects approach the participant as well as object velocity differences between the eyes.

We thus decided to elicit vection using an optic flow field that provided additional motion information when combined with binocular vision. Object layers of various distances to the viewpoint provided relative motion information (i.e. far objects move slower relative to close objects) in conjunction with disparity information for each layer. A stereoscopic projection system (see 2.2.1.1) was then used to present the optic flow field binocularly to our participants.

1.2.3.4. Dynamic viewpoint

Dynamic viewpoint rendering in VR has shown to benefit vection. Lowther & Ware, 1996; and Prothero & Parker (2003) showed that vection latency was greater when participants moved their head in front of the display on which the motion stimulus is presented compared to when participants remain absolutely stationary under

otherwise identical stimulus conditions. When dynamic viewpoint renderings were used, the increase in vection latency for moving participants was mitigated. This effect can be explained by a discrepancy between biomechanical, somatosensory and vestibular motion cues and vision, that is - the visual stimulus is not properly updated during self-motion as it would be during natural viewing conditions.

Visual parameters such as a correct perspective, adjusted FOV and updated object-to-object relationships of the rendered scene may change the way we perceive the display. Correct renderings of the view may help participants to perceive the visual stimulus embedded in an allocentric frame of reference and thus facilitate convincing self-motion illusions. In effect, the use of this dynamic viewing frustrum allows participants to perceive the projection as a window (defined by the screen boundaries) into a stationary, virtual world rather than a flat image of the world on a screen (possibly perceived in body coordinates).

The overall consensus is that dynamic perspectives under stereoscopic viewing conditions afford increased convincingness of the depicted scene, richer relative depth cues, better depth separation between foreground-background layers and thus, increased quality of vection and a sense of presence compared to conventional 2D/3D viewing conditions.

In our study, we investigated conditions where participants experienced physical motions to conditions during which participants were stationary. Head and torso movements in the motion conditions could have resulted in reduced vection in absence of dynamic perspective and FOV renderings. Thus, adding physical motion cues in the motion conditions would not have been the only factor responsible for the outcome of vection experiences. To address this confound and overall facilitate vection, dynamic perspective and FOV renderings were necessary and implemented accordingly; see subsection 2.2.1.1 for more detail.

1.2.3.5. Relative motion cues

Physical changes to the viewing setup have been known to enhance vection as well. For example, an effective method to provide relative motion cues is to introduce a physical, stationary foreground object in front of the display or projection screen that

depicts the motion stimulus. Relative motion cues can be beneficial for low velocity conditions where vection is usually difficult to elicit and can be effectively used with large FOV displays such as curved, cylindrical or spherical display systems as they typically lack sufficient relative motion cues. For example, Howard & Howard (1994) demonstrated that placing vertical bars in front of the screen is sufficient in enhancing circular vection for angular velocities as low as 5°/s. Similarly, Lowther & Ware (1996) placed a 5x5 grid in front of the display and they found that this addition facilitated vection as well. These findings suggest that a multi-panel display system may inherently provide relative motion cues as the grid is made up of the display bezels. Riecke, Schulte-Pelkum, Caniard, & Bulthoff (2005) took a slightly different, simplistic yet effective approach. In experiment 2, they added almost unnoticeable scratch marks on a projection screen which sufficiently provided relative motion cues to facilitate vection. In practice, relative motion cues can be provided by an ecologically valid application metaphor such as, for example, a cockpit used for operator training which may additionally benefit the overall user experience and attractiveness of the setup.

In the context of our study, we designed the viewing setup (see 2.2.1.1) so that it could pass as cockpit of a vehicle travelling through an environment with the participant within it. The screen and participants were fully enclosed and a dynamic view frustrum system provided them with additional relative motion information through the rendered scene. Similarly to a vehicle, the screen was surrounded by a frame structure so that viewing onto the screen appeared somewhat like seeing through a windshield mounted on the frame (i.e. the a-pillars of a vehicle).

1.2.3.6. Cognitive factors

It has traditionally been accepted that bottom-up or stimulus driven factors as those mentioned above are instrumental in visual perception. Gibson (Gibson, 1966, 2002) formulated a theory of direct perception where humans solely rely on sensory information to trigger experiences. The theory is based on the thought that experiences are initiated on a sensory, or bottom (processing) level and that, as the signal travels linearly up the assumed processing pipeline, the data is subject to increasing complexity of assessment until the extracted information creates the ultimate state of experience. This processing model is known as data-driven or *bottom-up* processing. Gibson's

theory explains why we can quickly and accurately perceive our environment under ideal viewing conditions.

Shortly after Gibson published his theory, Gregory published a theory of indirect perception which is based on the idea that we construct our perceived environment by learning, previous experiences, knowledge and other cognitive factors (constructivism) (Gregory, 1970, 1974). He argues for a perceptual system that is based on hypothesis testing where underlying processes of perception have access to ambiguous and largely limited information as most of the information that reaches our higher brain functions are either filtered out or not fully captured by our senses. He suggests that, based on filtered information, our perceptual system uses estimations and "best guesses" or principles of likelihood. This "*top-down*" theory explains why we can (quite effectively) perceive our environment under less-than-ideal sensory conditions.

More recent evidence points to an interaction between lower- and higher-level processes instead of proving the exclusivity of either one. Tulving & Schacter (1990) proposed that our perceptual system adaptively relies on a *combination of mechanisms* based on stimulus information. For example, if the stimulus information is high, it tends to rely heavily on bottom-up or sensory-driven mechanisms and when sensory information is low, it relies on top-down processes. In the context of vection, bottom-up factors have traditionally been the focus of investigation, but higher-level processes have recently received attention and found to be likewise instrumental. In the following subsection, relevant cognitive factors are elaborated.

1.2.3.6.1. Frame of reference

Establishing a stable reference frame is seen as crucial for self-motion experiences. Gibson (1954) stated that there is no self-motion perception without a stationary and stable space or environment. Based on a framework proposed by Seno, Ito, & Sunaga (2009), Riecke & von der Heyde (2002) and later revisited by Riecke & McNamara (2007), establishing a stable reference frame is part of our adaptation to the environment we live in. In other words, we "learn" to accept our environment as being stable relative to us. Adopting a stable reference frame is then a result of action and perception within our environment to crate useful interactions and experiences within it.

For self-motion, we distinguish between a body-centered and an allocentric reference frame or rest frame (background or stable environment). Objects that are linked to the body (located in body coordinates) move with the observer whereas the background (such as mountains, lakes or clouds) is located in the allocentric reference or rest frame and is assumed to be stationary. Brandt et al. (1975) and Fischer & Kornmüller (1930) suggest that certain foreground objects are located in body coordinates which are thus perceived as moving with the observer.

An example are objects associated with a cockpit. Pillars around the screen, instruments and the like are perceived to be moving with the observer through a stable environment which is depicted on the screen. This effect can be reinforced when scene parameters on the screen are dynamically updated as a function of head motion. The screen then inherits the property of a “window” to an outside world. Motion in that window is then likely due to self rather than object motion. In contrast, if our head motion is not taken into consideration when rendering the scene, the display contents may appear as flat and perceived within body coordinates and as part of the cockpit, not as part of a stable environment.

To make self-motion more likely, one can foster the impression that the environment is stable by establishing a stable rest frame. For example, the structural property of a rest frame relevant to its perceived stability is the polarization, or orientation of objects that are affected by our concept of gravity or the gravito-inertial force-vector (Allison, Howard, & Zacher, 1999). That is, objects within our environment exhibit a certain visual polarity, such as furniture and boundaries of surfaces like walls, floors, pillars and ceilings. An ecologically valid orientation of scene objects can benefit the perception of stability for a given rest frame. While there are numerous factors governing the perceived stability of a rest frame and efforts that need to be undertaken to make it convincing, it takes surprisingly little effort to counter it. Destabilizing the effectiveness of a rest frame and thus destroying the perceived background motion (which induces self-motion) can be accomplished by introducing a stationary background object. This is especially effective when the stationary background object is located in the far periphery. While providing a stationary, peripheral background can reduce unwanted occurrences of vection artifacts and potentially related symptoms of motion sickness, it is a common source of vection suppression where a convincing self-motion

experience is desired (Prothero & Parker, 2003). For example, a visible, stationary background in the far periphery is quite common particularly in home entertainment such as 3D gaming. We propose that reducing ambient light or placing blinders around the viewing setup is fairly simple and could possibly heighten the overall user experience.

Within the scope of this study, three methods were used to facilitate the impression of a stable reference frame: Firstly, we excluded conflicting visual and auditory information from the stationary surround through the use of a blackout tent around the participant and projection system as well as a masking sound presented through headphones. Secondly and as mentioned in 1.2.3.4, the projection screen was more likely to be perceived as a window in body coordinates rather than a screen in the allocentric reference frame through the use of a dynamic view frustrum, similar to what one would encounter in a vehicle cockpit. Thirdly, we added a floor plane textured with grass to the optic flow field which made self-motion through an environment more plausible and natural.

1.2.3.6.2. Realism

In recent years, an increasing body of evidence on cognitive factors along technological advancements have guided investigations to directly look into the effects of “natural” versus abstract motion stimuli (Richards, Mulavara, & Bloomberg, 2004; Riecke, Schulte-Pelkum, Avraamides, et al., 2006; Schulte-Pelkum et al., 2003).

The question is, if we keep all relevant sensory, lower-level motion information such as spatial and temporal frequency and local image statistics constant across all conditions, does “naturalness” really play a significant role? For example, Richards et al. (2004) compared natural and abstract visual motion stimuli and their effect on postural adjustments associated with convincing self-motion perceptions. Participants were engaged in a treadmill walking task while presented with two visual motion stimuli on a projection screen. The two viewing conditions consisted of an abstract motion stimulus made up of a polka dot pattern and a “natural” viewing condition during which a simple, textured room was displayed that provided intrinsic upright cues compared to the polka dot stimulus condition. He observed that roll and pitch body adjustments were more pronounced during the “natural” viewing condition compared to the abstract condition. In line with his observations, participants reported that self-motion experiences occurred

more frequently and reliably during the “natural” viewing condition and that the overall vection convincingness was higher.

Unfortunately, the study had methodological limitations that made it problematic to identify “naturalness” of the depicted scene as the only factor that could have affected vection. While scene ecology was a factor in their methodological model, lower-level (bottom-up) factors were not. That is, two different conditions were compared that not only differed in their level of “naturalness”, but also in regards to their image information, such as spatial frequency or edge rate, foreground-background separation and possibly other motion information that could have affected vection. The supposedly facilitating effect of naturalness on vection may just have been due to stronger, lower-level motion information.

To disentangle motion information and “naturalness”, Riecke, Schulte-Pelkum, Avraamides, et al. (2006) directly compared two visual motion stimuli with identical motion information; one depicted a natural scene of a medieval market place and the other image showed a mosaic-like scrambled version based on the same image source material. They concluded that the naturalistic scene yielded improved vection experiences across vection metrics and pointed out that this result was especially surprising because the abstract “scrambled” image condition contained slightly higher spatial frequency content than the “natural” scene so that participants should have had a stronger sense of vection during the “scrambled” condition. They further investigated ecological aspects of “naturalness” with a stronger highlight on conditions of “naturalness”. Two scene conditions were compared based on an identical picture in both conditions, however, one scene was presented upright and the other upside down. The results showed that the upright scene and thus “naturalness” considerably increased the convincingness of self-motion and a sense of presence within the VR. They concluded that ecologically valid, naturalistic, scenes (which we are used to by experience) are important for eliciting convincing self-motion illusions and user experiences in VR. Their findings were later corroborated by Sato et al. (2007).

Based on their study, Riecke et al. (2006) outlined three main mechanisms that could be involved: Firstly, pictorial depth cues in the globally consistent, naturalistic scene may have increased the perceived distance to the stimulus which is known to

increase vection velocity (Wist, Diener, Dichgans, & Brandt, 1975). Secondly, for scenes comprised of a multitude of layered objects, background objects furthest away dominate self-motion perception (Seno et al., 2009; Ohmi, Howard, & Landolt, 1987). Foreground-background separation between the screen as foreground object (window) and the naturalistic scene as background further away may have indirectly facilitated vection, a result of the setup itself. Thirdly, the natural stimuli may have provided sufficient landmarks that are more plausible and being accepted as stationary. That is, observers may have established the scene as reference or rest frame which resulted in self versus object motion (Dichgans & Brandt, 1978).

Based on this evidence, we kept our optic flow based self-motion simulation as natural as possible. The scene used in our study was abstract, but not fully unnatural unlike the scrambled optic flow used in Riecke's study mentioned earlier. Our scene suggested travelling on a vast, grassy plane with an apparent horizon, but without any apparent landmarks. Layered, white dots of various shapes and sizes above and below the viewer suggest either under-water travel or snowing as casually reported by participants. Due to the dynamic view frustrum in conjunction with binocular vision used on our setup, the content on the screen was perceived as behind the screen as opposed to on the screen which afforded additional foreground-background separation in line with a window metaphor.

1.2.3.6.3. Affordances

During daily activities in natural environments, we can freely move about and experience self-motion as a result. We know the affordance of our body like abilities of moving within certain limitations and sets of possible actions we can perform within our environment. In VR, this cognitive aspect is especially important to consider as we attempt to provide the illusion of self-motion. The goal is not only to overcome sensory conflicts (such as conflicting vestibular or somatosensory cues), but also to reduce top-down or cognitive conflicts by convincing people, that they can, in fact move. This "trick" or "make-believe" allows us to "prime" observers for the experience ahead and hide the limitations of the underlying motion platform system. This idea of "suspension of disbelief" has already been widely adopted in the entertainment sector.

In the context of the vection literature, several vection studies allowed seating conditions with some freedom of motion to suggest that self-motion is possible. For example, Lackner and Väljamäe used rotatable chairs to facilitate circular vection (Lackner, 1977, Väljamäe, 2009). Berthoz et al. (1975) and Lackner (1977) seated participants on movable carts that allowed for linear translations to investigate linear vection. None of them, however, explicitly investigated the effect of movability on vection and thus no data on this particular matter was available. The question remained: does the plausibility of physical self-motion or “movability” facilitate vection?

In 1995, Lepecq and colleagues conducted one of the first studies investigating the effect of plausibility of self-motion for visually induced linear backward vection in a study where children of seven and eleven years of age were either seated on a stationary chair (self-motion implausible) or on a chair with rollers and were demonstrated the possibility of motion (self-motion plausible) (Lepecq, Giannopulu, & Baudonniere, 1995). They found that cognitive manipulation reduced vection latency for the self-motion plausible condition, yet vection occurrences remained the same. Wright and colleagues investigated, if this effect can be observed for elevator vection (self-motion in the up/downwards direction) as well (Wright et al., 2006). They found an increase in vection compellingness (but vection latency remained unaffected) when participants were demonstrated and seated on a vertical oscillator motion device compared to being seated on a stationary chair in another room. Riecke and colleagues followed a different approach and investigated whether a motor-driven hammock chair can enhance circular, auditorily induced vection after the chair rotations were demonstrated to the observer (Riecke, Feuereissen, & Rieser, 2009). To make self-motion plausible, participants were asked to either suspend their feet off the ground on a attached foot rest attached to the hammock (self-motion plausible), or leave them on the ground (self-motion implausible due to a solid connection between the body and the stationary floor). Plausibility of self-motion resulted in 20% higher vection intensity ratings, an upwards trend of vection convincingness, lower vection latencies (41s vs. 31s) and a marginal trend towards higher occurrences of vection (84% vs 68%). However, from this data, it is impossible to disambiguate whether this effect was solely a result of higher-level cognitive knowledge of the possibility of movability or lower-level perceptual somatosensory cues indicating stationarity.

Interestingly, there are examples in the vection literature where participants were presented with a seating paradigm that made physical motion plausible, but it had no effect on visually induced (circular) vection in terms of vection latency, intensity and convincingness (Schulte-Pelkum, 2007, Schulte-Pelkum, Riecke, & Bülthoff, 2004). Differences in the setup and other factors could have been accountable for these contradicting findings and are discussed in Riecke (2009). It is not always obvious whether cognitive or perceptual influences are at work in vection studies and thus further, focused research as to how, why and under what circumstances these aspects facilitate vection is necessary.

As a necessity of our experimental procedure (see 1.2.3.7), participants were seated on a chair that allowed for minimal physical motion cues. The chair was demonstrated to participants before the study and for them, physical self-motion was plausible. However, we did not specifically investigate whether or not plausibility of physical motion affected vection in our study.

1.2.3.7. Multimodal stimulus conditions

Under natural, daily conditions of self-motion, we perceive our surrounds and self-motion through almost all our senses. It is believed that our perceptual system is highly multimodal. Motion cues seem to be processed and integrated across different sensory modalities at a very early processing stage (Bremmer, 2005) and then integrated into a unified perceptual representation. Although the integration of sensory and motor information about self-motion is not well understood, it is likely that internal models in our brain are multimodal (Mergner & Rosemeier, 1998, Wiener, Berthoz, & Zugaro, 2002, Wolpert, Ghahramani, & Jordan, 1995, Ghahramani, Wolpert, & Michale, 1997). Specifically, our brain may integrate cues from various sensory modalities into a coherent model of self-motion based on sensory weighting, filtering and augmentation to extract useful and coherent motion information and to disambiguate sensory conflicts (Ghazanfar & Schroeder, 2006).

Our perception of self-motion seems to rely heavily on vision to the extent that vision dominates over other senses especially in situations of sensory conflicts (Soto-Faraco, Spence, Lloyd, & Kingstone, 2004; Soto-Faraco, Kingstone, & Spence, 2003). For example, Lishman (1973) and later Sun, Campos, Young, Chan, & Ellard (2004)

demonstrated that when optic flow specifying linear self-motion was put in competition with vestibular inputs, it tended to dominate them, even in cases of extreme discrepancy. Substantial navigation errors can be observed if we rely on vestibular cues exclusively (Durgin et al., 2005). It seems multimodal self-motion perception is necessary to augment vestibular cues because the vestibular system only reacts to accelerations and thus proves to be a noisy estimator of velocity (Schaffer & Durgin, 2005).

In context of the vection literature, there is evidence that combining motion cues from different senses can be beneficial. For example, Riecke demonstrated that auditory cues on their own are quite weak to induce vection (20-75% vection occurrence), but they can effectively facilitate visually (Riecke, Väljamäe, & Schulte-Pelkum, 2009) and biomechanically (Riecke, Feuereissen, & Rieser, 2010) induced circular vection. In the case of the latter, user-generated motion cueing may have been beneficial to some extent. For example, Berger, Schulte-Pelkum, & Bülthoff (2010); Riecke (2006) and Schulte-Pelkum (2007) in experiment 5 showed, that small yet qualitatively motion cues, whether actively or passively applied, can enhance visually induced vection. They found that the quality (i.e. direction) and the correct timing between the visual and vestibular/somatosensory motion cues are sufficient to create a salient multimodal self-motion experience despite mismatching qualitative parameters such as acceleration and velocity. This suggests that we are tolerant to visuo-vestibular discrepancies within certain limits which is especially useful for affordable, inertial simulations such as used in operator training simulators (Van der Steen, 1996).

Furthermore, the benefit of using multimodal stimuli has been stressed by both, Riecke et al. (2010) and Schulte-Pelkum (2007) [experiment 6], who found that added sensory modalities facilitated vection significantly more when combined compared to adding up the degree of facilitation taken for each modality individually. Riecke referred to this phenomenon as super-additive or synergistic effect. This effect found during the two studies is especially intriguing since only simple cues such as jitter, jerks or vibrations were additionally provided. It is thus advantageous to consider simple motion cues and even binaural audio renderings especially for flight or driving simulations. The simple and creative use of adding additional motion information through various sensory modalities to the simulation can provide cross-modal and cognitive benefits at minimal effort and cost yet significantly benefit the overall simulation effectiveness.

These findings prompted us to explore cross-modal benefits in our study by combining visual and vestibular/somatosensory motion cues with the aim to augment visually presented motion information and reduce conflicting cues from the vestibular system (see also 1.2.3.9). We specifically investigated these cross-modal cue combinations through the use of a novel gaming chair that allowed small tilting motions of the seating surface (see subsection 2.2.3).

1.2.3.8. Effects of interactivity on perception

Traditionally, vection has been investigated by a stationary observer being passively exposed to a motion stimulus, such as visually moving along a predefined trajectory. However, contemporary applications such as flight or driving simulators require user interaction to actively control acceleration, velocity and direction. Surprisingly little is known about how user interaction affects vection during these conditions.

While Riecke (2006) used active control paradigms for self-motion through his VR, this aspect was not explicitly investigated. In fact, the author has not found any reports in which user interaction was directly investigated. However, there is some related evidence that interaction may influence the way we perceive our environment. For example, Wexler, Panerai, Lamouret, & Droulez (2001) found, that active observers perceive spatial attributes of objects differently. That is, while participants passively exposed to perspective changed within a scene, they perceived object of the depicted environment as rigid whereas participants actively changing their perspective perceived objects not only as rigid, but also as stationary and embedded into the allocentric reference frame which helps to establish a rest frame, an important aspect of effectively eliciting vection.

Furthermore, user interactivity may result in higher activity compared to passive viewers which may result in additional internal cues such as afferent motor commands and re-afferent vestibular/proprioceptive self-motion cues (Mittelstaedt & Mittelstaedt, 2001) or other, positively modulating effects on vection (Trutoiu, Streuber, Mohler, Schulte-Pelkum, & Bülthoff, 2008). Along the lines of thought expressed in Mittelstaedt & Mittelstaedt (2001), Crowell, Banks, Shenoy, & Andersen (1998) suggested that additional, non-retinal cues may facilitate self-motion perception for head turns. They

found that motor efference copies for head turns, neck proprioception and vestibular canal stimulation contributed to an accurate perception of self-motion judgments during active vs. passive head turns.

Although not investigated in our study, it is interesting to note that interactivity may also affect occurrences of motion sickness. Evidence suggests that actively controlling one's own locomotion can mitigate effects of motion sickness. Rolnick & Lubow (1991), for example, investigated why drivers themselves usually don't experience motion sickness and conducted one of the first studies that formally looked into the relationship between user control over a motion stimulus and motion sickness. They found that observers exposed to nausogenic rotations reported significantly reduced effects of motion sickness when allowed to control their motion compared to those who were passively exposed to self-motion without an option to intervene. However, future work is needed to confirm and extend their findings in the context of vection in virtual environments.

In our study, we directly compared conditions of passive stimulus exposure to conditions of user intervention based on a traditional joystick and an embodied motion control paradigm. The purpose of this experiment is to find out, if user intervention can enhance vection and the experience within artificially generated environments. We aim to investigate interaction paradigms, their implementation and their effects on the user experience in the contest of our VR setup. We hope to formulate suggestions or considerations for future, interactive systems where locomotion and a convincing sensation thereof are desirable.

1.2.3.9. Vestibular dysfunction

As our self-motion perception seems to be multimodal in nature, there are facilitating and conflicting cues when experiencing vection due to absence of physical self-motion. Conflicting cues usually emanate from the vestibular system that does not register any inertial motion cues in stationary observers who are visually or through some other modality exposed to a motion stimulus.

This dissonance is normal for participants who have a healthy vestibular system. For example, Cheung, Howard, & Money (1991) found that visually induced vection can

cause significant discomfort in healthy observers, most likely due to conflicting vestibular cues compared to those who are not. Johnson, Sunahara, & Landolt (1999) and Kennedy, Drexler, & Kennedy (2010) for example, investigated the effect of vestibular impairment on vection and found that bilaterally labyrinthine defective observers exhibit lower vection latencies, greater magnitude of vection, greater likelihood of motion sickness under certain conditions and unambiguous roll or pitch vection during conditions of visually induced vection.

Thus, in studies that generalize to a population of healthy participants, care needs to be taken to select those participants who have no vestibular impairment so that the experience and reporting of vection is similar between participants and typical for healthy ones. Mixing both healthy and impaired participants in the context of their vestibular function can severely limit the power and internal validity of a vection study.

For the participant pool used in our study, all possibly affected participants were screened out before the study. We used the Romberg test (Khasnis & Gokula, 2003), an established screening method to systematically exclude participants with balance impairments that could be the result of a dysfunctional vestibular system. This procedure, however, limited the scope of our investigation to a “healthy” population only.

1.2.3.10. Limitations and challenges

The perception of self-motion in the context of sensory disambiguation and selective cue combination can result in dissonances between available information about self-motion from various senses and missing behavioral (re-) actions that would naturally accompany locomotion (such as postural adjustments, for example). Limitations in form of side effects as a natural response to these unnatural dissonances and behavioral changes are commonly observed in conditions of self-motion simulation and vection.

These side effects are termed motion adaptation syndrome, motion sickness (Irwin, 1881) or cybersickness (McCauley & Sharkey, 1992) and were found to co-incide strongly with instances of vection (Stern, Koch, Stewart, & Lindblad, 1987; Uijtdehaage, Stern, & Koch, 1992). Their form and intensity depend on the individual who experiences the self-motion simulation and the type of stimulus condition.

General, observable effects are postural disturbances, negative perceptuomotor side effects and aftereffects. Cardinal, pathognomonic signs include changes of skin color, cold sweating especially on the insides of the hands as a result of acute changes in sensory input, nausea and vomiting. Associated signs include salivation, headache, drowsiness, dizziness, increase in perceived body temperature, general malaise, apathy and depression. Severe associated signs may include disruption of perceptuomotor control such as decreased motor coordination or even loss of consciousness (Harm, 1990; Lestienne, Soechting, & Berthoz, 1977; Reason & Brandt, 1975; Reason, 1978). Self-motion simulations that rely heavily on visual motion stimuli typically induce non-gastric, head-related effects such as dizziness, vertigo, blurred vision, eyestrain and headache (Havron & Butler, 1957; Kennedy, Berbaum, & Lilienthal, 1997). About 50%-100% of observers are affected by these effects under conditions of visual self-motion simulation. Typically, gastric effects can be observed in 20%-60% of observers in form of nausea or vomiting (Crampton & Young, 1953; Lawson, Graeber, et al., 2002) and approximately 30% of observers exposed to self-motion simulations in VR experience symptoms severe enough that their exposure to the simulation has to be prematurely terminated.

For the use of VR simulators generally and vection in particular, these implications severely limit their usability. Occurrences of motion sickness may result in distorted perception, distraction from the task, discomfort and violation of the observer's right to well-being and as such, assumptions, data and other relevant aspects of the study or simulation have to be taken with caution when severe symptoms of motion sickness are reported.

Because motion sickness is of tremendous relevance to the field of vection, it is a heavily studied area and some frameworks and theories have been formulated towards a deeper understanding of the nature and underlying principles of motion sickness. A commonly accepted theory is the sensory conflict theory proposed by Reason & Brandt (1975) which was later revisited by Flanagan, May, & Dobie (2004) which in essence states that qualitatively and quantitatively conflicting motion information from various sensory modalities may cause motion sickness.

While this theory of conflicting motion information can explain some effects, many observed aspects of motion sickness do not fit the model. For example, a sensory conflict may not produce motion sickness reliably between individuals or within a given individual over time. To explain this effect, Riccio & Stoffregen (1991) formulated the theory of (prolonged) disruptions of normal postural control activities as additional means to explain motion sickness occurrences and criticized the shortcomings of the sensory conflict theory (Stoffregen & Riccio, 1991). Both theories however, do not fully capture and explain the phenomenon of motion sickness in real and virtual environments and more investigations are necessary as there is at present no unifying framework that can explain all the physiological manifestations of motion sickness and ultimately help us to effectively mitigate motion sickness.

Despite our limited understanding about the underlying mechanisms of motion sickness, several methods to address the challenge of mitigating motion sickness have been investigated. For example, while biofeedback and autogenic feedback practices were less effective (Cowings, 1990; Jozsvai & Pigeau, 1996), adaptation though regular exposure to vection (Hu, Grant, Stern, & Koch, 1991), deep breathing (Jokerst, Gatto, Fazio, Stern, & Koch, 1999) and electro- acupressure techniques (Hu, Stritzel, Chandler, & Stern, 1995) have shown promising results.

Tough the focus of our study was on eliciting vection, we followed best practice to ensure participants remained comfortable during the remainder of our experiments. We frequently asked them about how they feel and made room for little breaks and refreshments to keep severe symptoms of motion sickness at bay. We decided to immediately excuse any participants from the study who reported severe signs of motion sickness.

1.2.3.11. Risks

Even though vection can be exhilarating and compelling, it can be quite disturbing and dangerous, so careful steps need to be undertaken to control for vection either where it is desired, with adequate steps to ensure the wellbeing of participants, or where it not. The danger of vection lies in the possibility that symptoms frequently do not cease with the motion stimulus and possibly linger after the observer has theft the motion simulator (Crampton & Young, 1953; Lackner & Teixeira, 1977). A common

correlate to vection is adapting to re-arranged perceptuomotor relationships within the VR and then a re-adaptation to perceptuomotor/spatiotemporal parameters of the real world. The latter may not be so obvious in cases of possibly unintended occurrence of vection compared to conditions where motion platforms are used.

It is strongly believed that lingering post-exposure effects have to be taken into account to ensure the safety of participants (Stanney, Kennedy, Drexler, & Harm, 1999). While participants are normally under the supervision and in relative safety during the stimulus condition, they may be at great risk after the exposure once on their own and under the influence of post-exposure effects. It is thus important that researchers or staff consider the influence of motion aftereffects, altered behavioral patterns and disruption of perceptuomotor control on participants. As Kennedy suggested, a safety protocol should be in place to address these issues and prevent harm as well as forthcoming liability issues (Kennedy, 1996). For example, participants should be allowed enough time for re-adaptation under supervision before they continue with their daily activities that could possibly be dangerous in the case of operating machinery, vehicles or other hazardous activities.

As Virtual Reality devices become more affordable, widely spread and effective (especially in their potential to induce vection), so will the frequency of exposure to risk, the severity of symptoms and their outcomes. Managing risks by avoiding motion sickness and post-exposure effects in the first place as well as allowing sufficient and effective adaptation/re-adaptation as a safe transition between environments should be a crucial part in our investigative endeavors.

Following best practice, we decided to closely watch the behavior of participants from the beginning to the end of our study. Breaks were enforced when necessary and participants and experimenter spent some time with the participant after the experiment for a short interview and casual conversation. The experimenter used this debriefing phase to allow the participants to re-adapt under supervision and to ensure they were reasonably well before they left the laboratory.

1.3. Hypotheses

The work of this thesis was inspired by questions that arose from looking at a previous vection study where participants were seated on a wheelchair and either used mouse buttons, a joystick or a combination of small, user-generated wheelchair turns/forward-backward translations to navigate through a naturalistic 3D world (Riecke, 2006). Participants viewed their locomotion through space on a curved projection screen and were instructed to closely follow a follow-me object that travelled ahead of them through the world. By doing so, participants travelled along pre-defined trajectories with varying curvature (one straight path segment and two curvilinear paths). Riecke used common, introspective vection measures such as vection latency and intensity that were verbally reported by participants. Before the study, he used a short training phase to familiarize participants with the procedure and then exposed them to a combination of trajectories and interface devices. The goal of the study was to investigate how path curvature and interface device affected common vection metrics and he found that input devices predominantly affected all measures in that the wheelchair condition showed lower vection latencies and higher vection intensity ratings compared to the button or joystick paradigm. The joystick and button press metaphor performed second best and there was surprisingly no difference between the two. Interestingly, Riecke found that trajectory had a less predominant effect on vection (see subsection 1.2.3.2 for effects of turn velocity/trajectory on vection) and found that only vection intensity was higher with greater turn velocities. The study opened up 4 questions that were addressed in this thesis and further elaborated in the subsections below.

1.3.1. Does turn velocity affect vection?

Higher turn velocities are known to enhance vection. Specifically, narrower turns seem to yield to a stronger sense of vection and potentially earlier occurrences thereof (Allison et al., 1999; Riecke, Schulte-Pelkum, Avraamides, et al., 2006; Riecke, 2006; Trutoiu et al., 2009; Wong & Frost, 1981).

In the vection literature, this effect was heavily investigated in the context of naturalistic scenes that were presented using various techniques. For example, Riecke and colleagues used a curved projection screen in conjunction with a traditional, non-

stereoscopic projection system to present a naturalistic environment through which participants travelled on trajectories with varying curvature (Riecke, Schulte-Pelkum, Avraamides, et al., 2006; Riecke, 2006; Trutoiu et al., 2009). Allison et al. (1999) on the other hand, used a physical mockup of a room that was built in a structure that rotated around participants roll axis.

Few studies directly compared the effect of turn velocity on vection for straight paths and turns of various degrees under conditions of optic flow. Trutoiu et al (2009) compared linear and curvilinear vection in the context of optic flow in the form of a highly abstract star field and found that greater turns resulted in greater convincingness ratings, particularly vection intensity. This contribution to the field is helpful because comparing findings across different studies may prove problematic due to differences in setup and stimulus parameters used.

Furthermore, the effect of varying curvature on vection has not yet been extended to the cases of more naturalistic optic flow conditions when perspective renderings and binocular motion information are available. A possible reason is a recent shift in the field from abstract motion patterns produced by mechanical devices to immersive, virtual reality systems.

Investigating turn velocities under conditions of optic flow at a constant translation velocity may give us parameters around how modern simulation scenarios can be designed for effective self-motion simulation. This may possibly be relevant to designers of current VR applications that need to make informed choices about their 3D implementation. Our aim is thus to extend the scope of existing knowledge from traditional setups to these increasingly popular VR display practices.

Our hypothesis is that if participants experience narrow turns and are thus exposed to a potent motion stimulus, their perceived self-motion experience is more intense, they perceive vection earlier and are more likely to perceive vection compared to conditions of small or no turns at all (lower degree of visual motion). We expect this effect to maintain its trend as outlined in literature because the vection inducing stimulus should remain its relative vection inducing power regardless of additional binocular self motion information.

In two experiments, we tested this hypothesis by exposing participants to an optic flow field that was animated at an constant translational velocity but at turn velocities of 8°/s and 24°/s (experiment 1, training) and 0°/s, 8°/s and 24°/s (experiment 2, main study) under otherwise identical stimulus conditions. Note: 0°/s turn velocity at any given translational velocity greater than 0°/s results in straight, forward motion. Thus 0°/s is synonymous for a straight path whereas 8°/s and 24°/s are paths with a wide and a narrow turn respectively. In each trial, participants reported the quantitative measure vection latency and intensity during the experiment. Qualitative data was collected in a post experimental interview, where participants rated what type of trajectory (straight or curved) was experienced as more intense and by how much.

1.3.2. Does physical motion cueing facilitate vection?

Although scarce, the vection literature provides evidence that small, physical motion cues can facilitate linear and curvilinear vection where the seat is either mechanically actuated (Berger et al., 2010; Schulte-Pelkum, 2007 [experiment 5]; Wong & Frost, 1981) or where participants themselves apply motions to the seat to locomote (Riecke, 2006). Additionally, the possibility of moving in the seat may aid in perceiving self-motion illusions based on a cognitive-perceptual framework of movability (Lepecq et al., 1995; Wright et al., 2006); see 1.2.3.6.3.

Various approaches have been used such as motion platforms (Schulte-Pelkum, 2007 [experiment 5]) or the previously mentioned wheelchair (Riecke, 2006) to enhance linear or curvilinear vection respectively. Vection latency in particular (Riecke, 2006; Schulte-Pelkum, 2007 [experiment 5]; Wong & Frost, 1981) and vection intensity (Schulte-Pelkum, 2007 [experiment 5]) seem to be affected by motion cueing with lower latencies and higher intensity ratings in conditions of motion cueing over no motion cueing thus clearly indicating the existence of a crossmodal benefit.

However, from the comparisons between interface devices in Riecke (2006), it was not fully evident whether the difference between the wheelchair and the other two paradigms was due to factors of usability or due to the physical motion cueing inherent to the wheelchair paradigm that could have provided additional, vestibular motion cues and reduced conflict cues present during the button and joystick conditions. In order to

specifically investigate this difference, we disambiguated physical motion cueing and investigated conditions of motion cueing versus no motion cueing.

To go further, we tested whether the benefit of the wheelchair motion paradigm used in Riecke's study was applicable to commercially available gaming devices such as simple and affordable gaming chairs. If so, attractive and cheap off the shelf hardware could be utilized to enhance self-motion experiences for various applications and settings, including the average living room. The idea behind exploring new ways of interacting in VR is to ultimately find perceptually effective methods that guide the design of affordable motion simulators. We thus replaced the wheelchair with a gaming chair to provide participants with slightly different, physical motion cues that remained congruent to the visual motion information. Unlike the linear forward/backward motion cues used in Schulte-Pelkum (2007) [experiment 5] or turns (yaw) in conjunction with linear forward/backward translations as in Riecke (2006), the gaming chair used here allowed for left/right, forward/backward linear motion cues so that the upright, seated body moved like the handle of a joystick, see 2.2.3.

Our Hypothesis is that if crossmodal benefits for congruent motion cueing as observed in (Wong & Frost, 1981) are at play, participants should report lower vection latencies and higher vection intensity ratings for conditions of physical motion cueing compared to conditions of no physical motion cueing.

In two experiments, we directly compared no motion cueing and motion cueing conditions with otherwise identical or closely matched visual motion stimuli. To investigate the benefits of motion cueing on optic flow based vection participants either just watched the optic flow in a rest position during the no motion cueing condition or were mechanically moved in the chair congruent to the visual motion stimulus (motion cueing condition). Quantitative measures were collected identically to 1.3.1. Additionally, in a post experimental interview, we asked participants how they felt about the motion cueing used in the study and to rate their perceived vection intensity for the two conditions; see subsection 2.3.6.

1.3.3. Is active, user-guided locomotion beneficial over traditionally passive locomotion conditions?

While actively (i.e. walking) and passively (i.e. riding a train) experiencing self-motion in the real-world is quite convincing, this may not be the case in VR. Actively controlling one's locomotion through VR is an integral task in gaming or vehicle operator training and to best of the author's knowledge, there are no direct comparisons between active and passive locomotion control conditions in the context of vection. In the vection literature so far, passive locomotion, for example Berger et al. (2010), Schulte-Pelkum (2007) [experiment 5], Wong & Frost (1981) and active locomotion such as described in Riecke (2006) have been investigated separately and a direct comparison between studies proves problematic at best due to the different stimulus conditions and methods used.

Even though we do not know how active versus passive locomotion control directly compares side-by-side, evidence from related fields may help us to hypothesize a relationship between interactivity and vection. For example, Wexler et al. (2001) may suggest that actively changing ones viewpoint could possibly help in establishing a stable, allocentric (rest-) frame that in turn could be beneficial for vection because it is believed that vection is mainly possible due to an assumption of a stable environment (Helmholtz, 1896). Crowell et al.(1998) and Mittelstaedt & Mittelstaedt (2001) suggest that active movements seemingly result in internal motor commands (efference and re-afference copies) that may provide additional motion cues to the participants. Interesting to note in this context although not explicitly tested in our study, Rolnick & Lubow (1991) suggest that active locomotion control could mitigate effects of motion sickness in conditions of visual and vestibular self-motion simulation.

The findings of this study may possibly be helpful to inspire future research towards new theories about how we perceive vection in the context of an action/perception loop that may allow us to approach VR design from a more informed perspective, especially in the context of user interaction paradigms.

We hypothesize that if interactivity results in additional, non-visual motion information, then we would expect that active locomotion control would yield a heightened sense of vection compared to passive conditions, at least for the vection

intensity measure. If the relative contributions of motion cueing remain the same, a similar trend will be observed for active versus passive motion cueing conditions.

To investigate effects of interactivity, participants were passively watching the motion stimulus in a stable resting position. This condition was compared to participants using a joystick to actively control the velocity and direction of the motion stimulus (their perceived self-motion). To investigate active versus passive motion cueing, participants were passively moved in the chair concomitantly to the visual motion stimulus for the passive motion cueing condition or actively leaned into the desired locomotion direction for the active motion cueing condition. Stimulus conditions were otherwise held constant. Quantitative data was collected as in 1.3.1. In a post experimental interview we asked participants how they felt about active and passive motion cues, what interface device they preferred (joystick or chair) and how they would rate their perceived intensity of vection for each condition; see subsection 2.3.6.

1.3.4. Joystick or gaming chair to control locomotion?

In the previously mentioned wheelchair study, Riecke (2006) modified a wheelchair to act as a gaming chair with great success. Participants found the wheelchair to be easy to use, very intuitive and they felt a high degree of control when using it in terms of its smooth response and accurate handling. In the context of vection, the chair afforded earlier vection onset and vection was perceived as more intense and convincing compared to using button press or joystick metaphors. If the wheelchair paradigm and the gaming chair paradigm we used in our study are similarly effective, it seems quite reasonable to accept that gaming chairs may replace traditional interface devices such as keyboards, mice and joysticks according to manufacturer claims.

If gaming chairs are a good alternative to joysticks, then participants should have a comparable level of control over their VR locomotion and prefer them over traditional joysticks.

To test this hypothesis, we compared conditions of joystick to gaming chair locomotion through an optic flow field in VR. Quantitative data was collected as in 1.3.1. In a post-experiment interview, we asked participants to rate overall vection intensity for

each condition and allowed them to sound their opinions about both interface devices in an open-answer fashion; see subsection 2.3.6.

2. Methods

2.1. Participants

Fifteen male and nine female participants (a total of 24) were recruited through the SFU Sona system, an online sign-up system in conjunction with hardcopy flyers and bulletins distributed around campus of the School of Interactive Arts and Technology in Surrey, BC, Canada. Additionally, craigslist ads for the greater Vancouver area were placed to recruit off-campus participants. The participant age range was between 18 and 45 years (mean = 24.75 years, *SD* = 6.86). All participants had normal or corrected-to-normal vision and no signs of vestibular dysfunction based on individually applied Romberg tests (Khasnis & Gokula, 2003).

All participants took part in both experiments. Experiment 1 and subsequently experiment 2 were administered in the same session that took about one hour. Participants were paid standard rates of $15 for their participation and were informed that they could terminate the experiment at any time with full payment of $15 without implications. We followed standard ethics procedures for the conduct of this study.

2.2. Stimuli and Apparatus

2.2.1. Visual information

2.2.1.1. The setup

The visual, stereoscopic motion stimulus was presented on a polarization preserving projection screen of 245 x 155cm in size. Two InFocus IN5504 located behind and above the observer projected two perfectly overlapping images with a resolution of 1920 x 1200 pixels each on the screen at a throw distance of about 3.4m. Each image was linearly polarized through filters directly mounted in front of the projector lenses. A 2.44 x 2.44 tent structure with sloping ceiling and covered by a

heavy, black curtain visually isolated the viewing range of the participants from the surrounding environment with the purpose to remove conflicting visual background cues. Additionally, ambient light was fully controllable. Figure 2-1 below depicts the described configuration.

Figure 2-1: (A) The IN5504 projector pair behind the tent. Note the polarizer panels mounted in front of the projector lenses. (B) The tent installation surrounding the screen and viewer. (C) A shot from behind the seat.

Participants sat on a Gyroxus gaming chair (see subsection 2.2.3) at approximately 1.30m distance to the screen which yielded a field of view of about 74 x 52 degrees. They viewed the stereoscopic image through suitable 3D polarizer glasses; see Figure 2-2 (A) below.

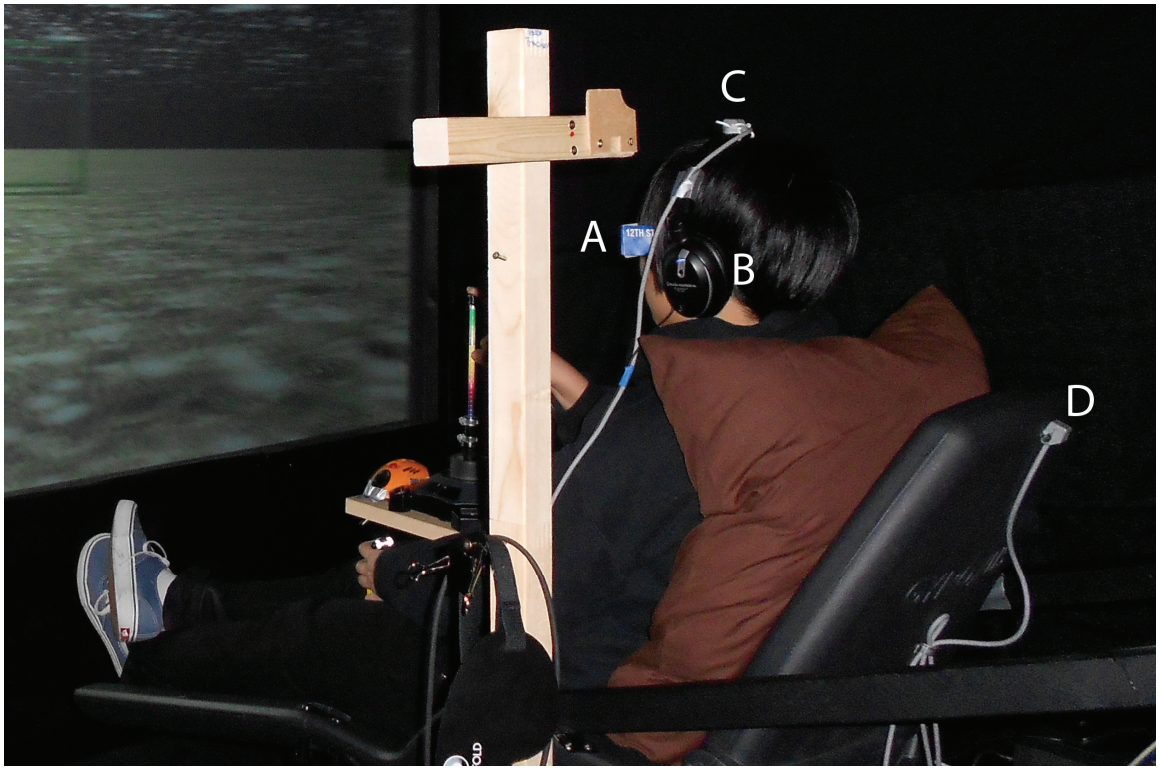

Figure 2-2: (A) Standard polarizer glasses commonly available at movie theaters or other 3D expositions. (B) AudioTechnica Headphones. (C) Tracker antennae mounted atop the headphone to register head motions (6DoF). (D) Tracker antennae to register chair motions.

To make the projected image more convincing in the context of vection, such as in Lowther & Ware (1996) or Prothero & Parker (2003) and to address possible confounds between conditions of motion cueing and no motion cueing, we adjusted the rendered perspective and FOV based on participant's head positions.

To thus realise a dynamic view frustrum on our VR setup, the head position and orientation relative to the projection screen was registered by a Polhemus Liberty tracking device (see Figure 2-3, Left) that continuously (240Hz) fed the head position and orientation (see Figure 2-2, C) to the simulation backend which then calculated the correct perspective adjustments and motion parallax.

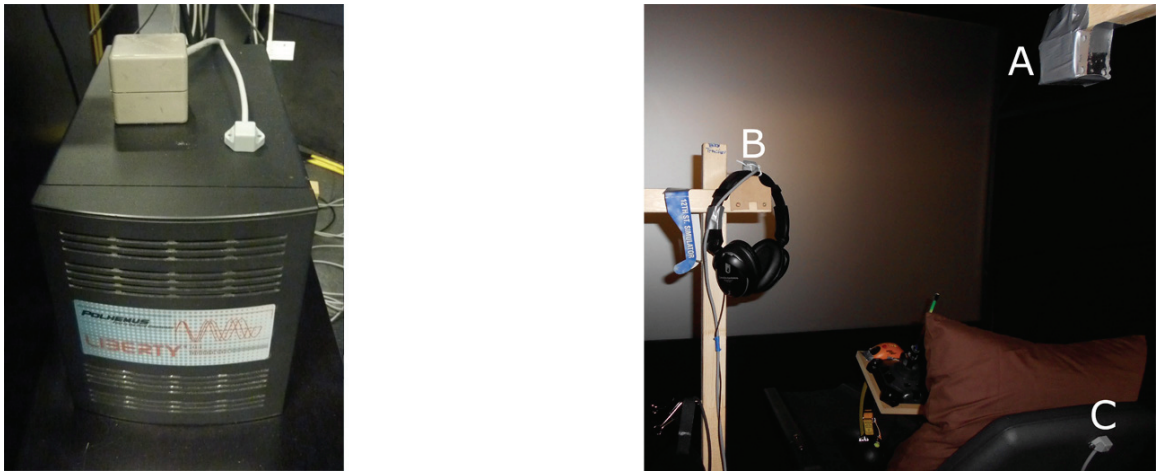

Figure 2-3: (Left) Polhemus Liberty 240/8 tracking system capable of tracking up to eight receivers at 240Hz. (Right) Tracking configuration. (A) Source unit transmitting a magnetic field. The source unit was mounted on the tent structure. (B) Receiver for the dynamic view frustrum. (C) Receiver to register chair motions (see also Figure 2-2 D).

2.2.1.2. The stimulus

As depicted in Figure 2-4 below, a simple, semi-abstract optic flow model was chosen to elicit vection. The model consisted of a simple, texturized floor plane that was visually placed on the same level as participant's feet. Layers of randomly distributed white dots resembling large snowflakes covered the floor plane and the black, virtual "sky". Eight of these optic flow layers were used in total to provide sufficient motion parallax between them. The distance between the lowest layer on the top and the upmost layer on the bottom was equal to the height of the screen. The model was void of any spatial features, such as landmarks or rendering artifacts. To address the latter, the far distance was excluded from the scene through the use of "virtual fog".

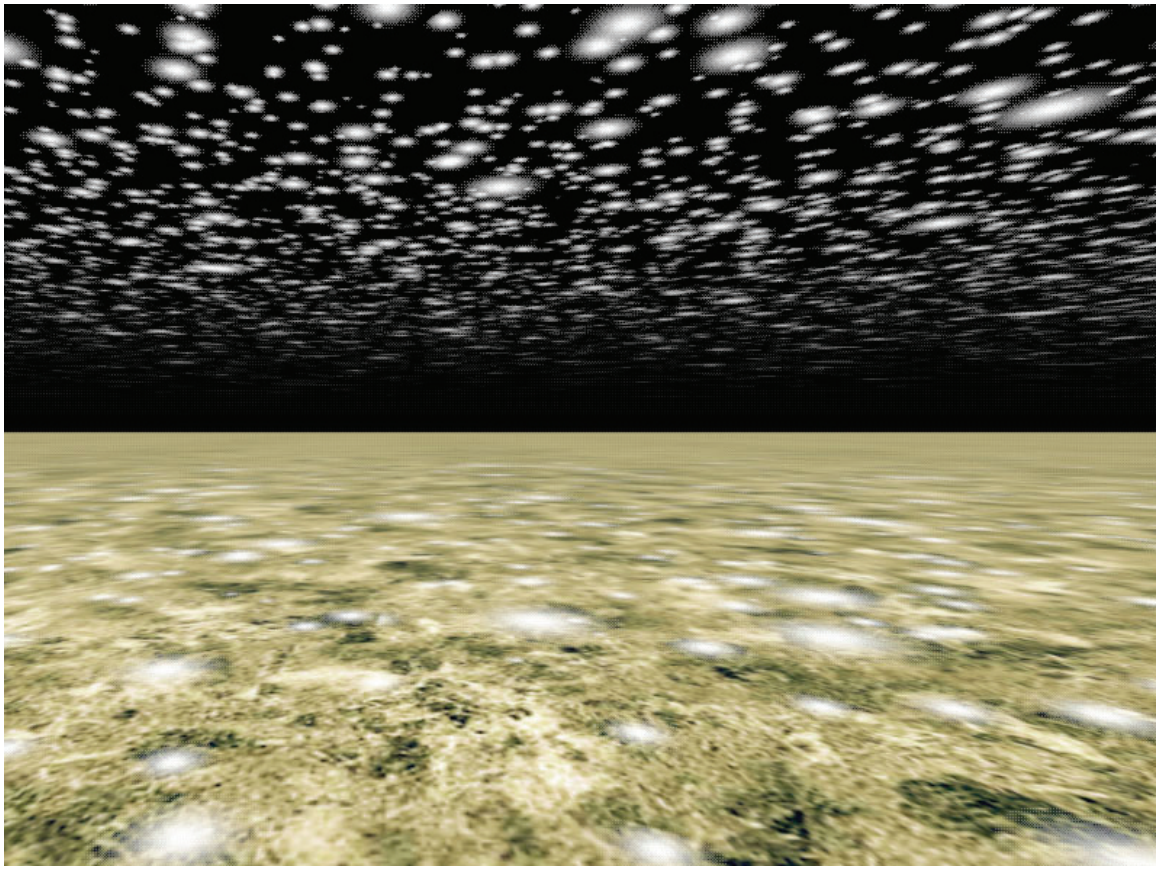

Figure 2-4: Optic flow model featuring texturized floor plane and layered dots below and above the viewing plane.

Participants travelled through the above mentioned virtual world on three types of paths that differed in the turn velocity which affected the resulting turn angle. To determine which acceleration, deceleration and turn velocity profiles produced sufficient optic flow yet minimized effects of motion sickness, we ran a series of pretests to identify these trajectory parameters beforehand.Table 2-1 below summarizes the trajectory parameters we found to be suitable.

	0° Turn velocity	8° Turn velocity	24° Turn velocity
Total turn angle (°)	0	192	576
Linear Acceleration (m/s^2)	1	1	1
Linear Velocity (m/s)	5	5	5
Rotational Acceleration ($°/s^2$)	0	8	24
Rotational Velocity (°/s)	0	8	24
Total Travel Distance (m)	140.8	142.3	142.0

Table 2-1: The three path parameters we used for our study. Note: Turns were symmetrical, thus parameters remained the same for left and right turns.

All trajectories we used consisted of a straight lead-in of 6 meters and a straight lead-out of 10 meters so that participants had ample space to accelerate and decelerate based on the parameters stated in Table 2-1. In-between the lead-in and lead-out paths, a 126 meter long trajectory was added that changed curvature based on the three conditions outlined in Table 2-1 above. The resulting trajectory thus had a 6 meter initial straight path segment for acceleration followed by a 126 meter straight (0°/s turn velocity), wide turn (8°/s turn velocity) or narrow turn (24°/s) followed by a 10 meter straight path segment for deceleration. A top-down view on the path geometry is provided in Figure 2-5 below.

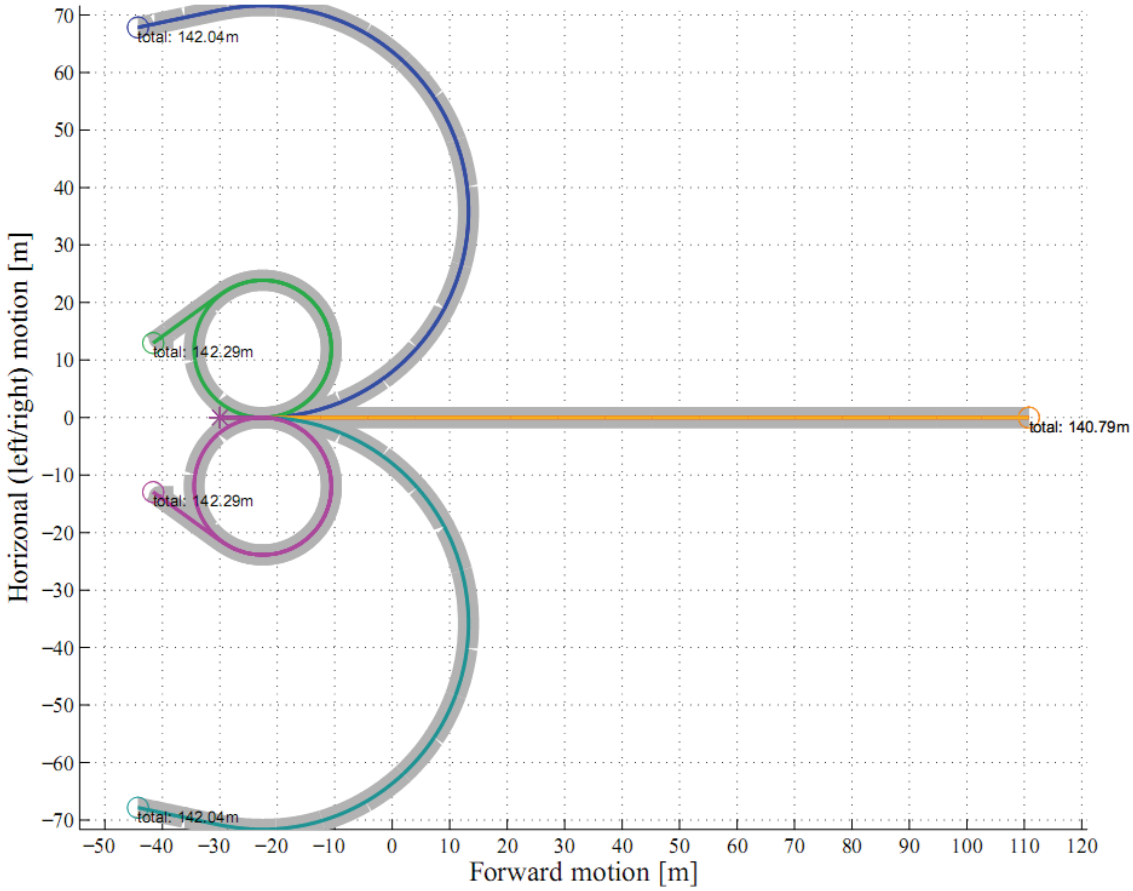

Figure 2-5: Top-down view on all trajectories.

Over the course of experiment 2, participants were presented with all trajectories depicted in Figure 2-5. In experiment 1, on the other hand, participants were presented with less trajectories because we designed it as a training phase and our aim was to keep the experiment duration within bearable limits for our participants. We excluded the straight path condition from experiment 1 and included only one turn direction for the remaining 8º/s and 24º/s conditions (for more detail, please refer to subsection 2.4.).

In order for participants to closely adhere to a predefined trajectory within each trial, a follow-me task was implemented that provided participants and the experimenter with the necessary means to precisely navigate on the trajectories. To that end, a green wire-frame cube was placed in world coordinates and animated along the predefined path. To provide feedback of how well participants were following the cube, a crosshair was placed on the screen (see Figure 2-6).

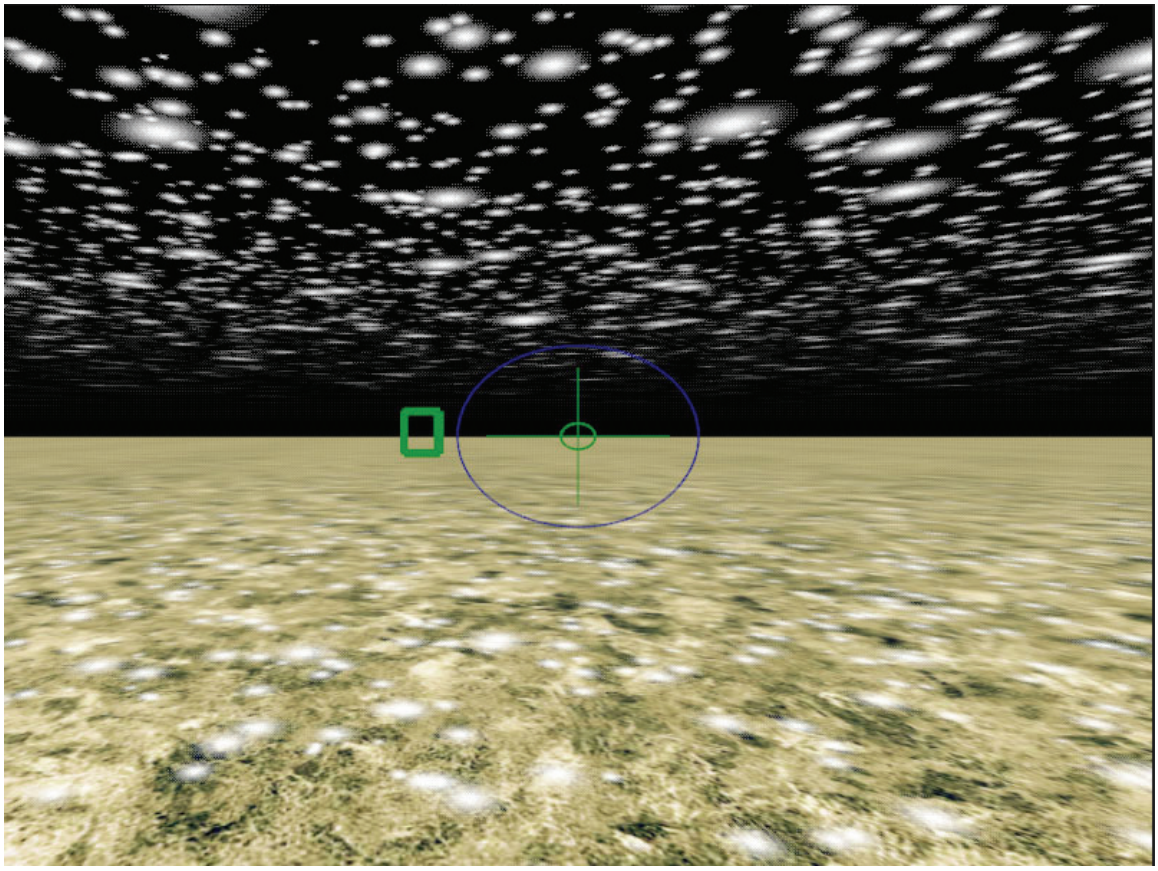

Figure 2-6: Trajectory guidance objects in the scene: the green cube (world coordinates) as a follow-me and fixation object. The crosshair was located in screen coordinates and the task was to align it with the cube within it.

The cube travelled with smooth accelerations and decelerations of 1m/s and a velocity of 5m/s either on one of four paths for experiment 1 or one of six paths for experiment 2, until it finished travelling on the predefined trajectory. The travel time for every trajectory regardless of turn velocity was 32 seconds.

Participants were instructed to closely follow the green cube and keep the green cube within the outer circle of the crosshair so that its edges almost touched the outer crosshair circle. We found this technique to be most effective in precisely following the trajectory. Participants as well as the experimenter received ample training in advance to execute this task sufficiently well. A training session is depicted in Figure 2-7 below.

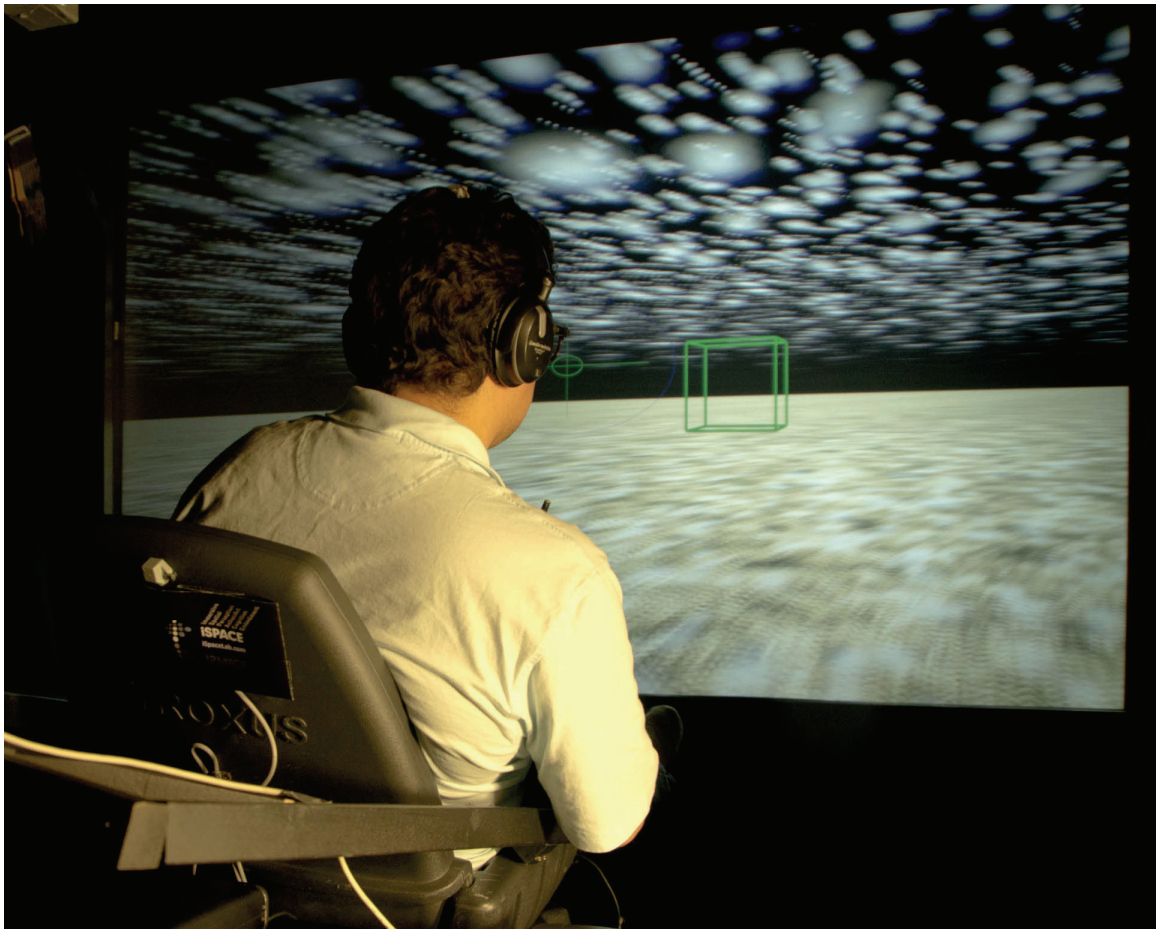

Figure 2-7: Participant attempting to closely follow the green cube through the stereoscopically depicted optic flow environment.

Besides guiding participants through the virtual environment, the cube served as a fixation object. Perceptions of vection may differ depending on where participants focus their eyes on within the visual scene and thus, participants were instructed to focus them on the cube to limit this variability. The cube also served as a suitable foreground object that may be beneficial in the context of visually induced vection (Fushiki et al., 2000).

2.2.2. Auditory information

Participants wore a set of AudioTechnica ATH-ANC7 noise cancelling headphones (see Figure 2-2 and Figure 2-7) to exclude ambient noise that could have interfered with visually induced motion cues and to present standardized instructions as

well as auditory alerts to participants. As masking sound, we presented various river sounds mixed together. We chose a naturalistic sound because we have found that it is less intrusive, less fatiguing and at least equally effective in masking ambient noise compared to pink noise and we have been successfully using this very sound in other vection studies as well. The volume was adjusted to moderate levels to sufficiently mask any background noise typically present in a dedicated lab space such as air conditioning units or other machinery. Audition was, however, not used to present motion information of any kind in our experiments.

2.2.3. Vestibular information and interfaces

Two interfaces were used to control locomotion through the virtual environment: a slightly modified Gyroxus gaming chair (see Figure 2-8) and a Logitech Attack 3 gaming joystick that was modified to suit our application (see Figure 2-12).

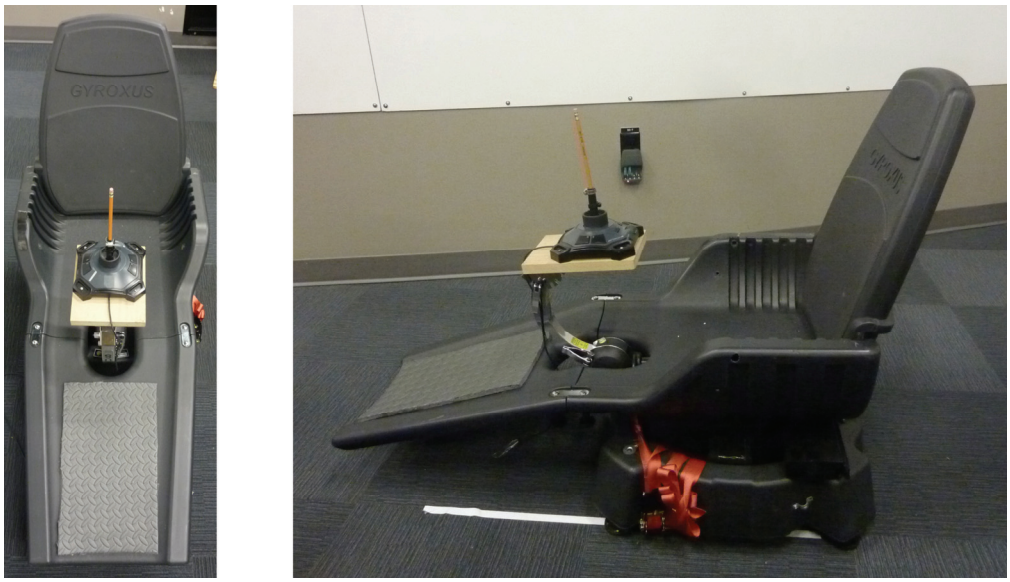

Figure 2-8: (Left) completely assembled product with joystick replacement. Note the adjustable backrest and removable, suspended footrest. (Right) Left view of the gyroxus gaming chair. Note the box underneath the seating surface resting on crossed metal ropes and the blocks/tie-strap to keep the seating surface stable during non-physical motion.

The Gyroxus gaming chair had a movable seating platform that allowed for vestibular cues as a result of head motion cues of about 20cm in the forward/backward and left/right direction. The degree of deflection of the seating surface controlled velocity

and the direction of deflection controlled the direction of locomotion in VR; see Figure 2-9. The upright position as depicted in Figure 2-8 above resulted in a full stop in VR. The Gyroxus motion paradigm as such was quite similar to the deflection of a joystick with the exception that the Gyroxus chair did not feature a re-centering force to move it back into an upright position when the leaning force was released. An upright user posture inherently puts the chair back into a somewhat neutral position. The torso and head of participants moved in a forward/backward, left and right tilting manner much like a pendulum. In effect, the range of motion becomes greater the further away from the seating platform motion is measured with its maximum at the head (about 20cm at the head vs. 10cm at the seating surface in each direction).

In pretests, we found that participants executed corrective head tilts to compensate for the head-tilt inherent to a leaning motion so that their head was generally parallel to the depicted floor plane.

Figure 2-9: The Gyroxus gaming chair affords leaning to control velocity and direction of VR locomotion.

To afford the tilting motions described above, the chair implementation consisted of 6 main components that contributed directly to the interaction paradigm: 1) a ring shaped base mount that contained two metal ropes going along each diagonal from corner to corner, thus crossing in the center of the base. This base was mounted on a wooden frame and did not allow for any movement. 2) a seating surface that rested on the diagonally crossed metal rope and was affixed to it, so that the seating surface could be tilted 10 cm into each direction (forward/backward and left/right). 3) a suspended leg and footrest mounted to the seating surface 4) an adjustable backrest that remained in the same position for all participants (a foldable pillow was used to keep participants in the desired seating position) 5) an adjustable steering rod that was kept in its default adjustment for all participants. The steering rod pivoted in a joint connected to the seating surface which in turn was connected to the base so that deflection of the steering rod also resulted in a tilt in likewise direction of the seating surface. 6) a game-pad mounted on a plate at the end of the steering rod, which was removed and replaced by a custom joystick setup for greater pointing accuracy and natural control.

Originally, the Gyroxus chair was factory-equipped with a potentiometer-based chair position sensing system, but came with an non-adjustable dead-zone (non-position sensing) around the upright position of the chair. Additionally, the potentiometers failed shortly after we have put the chair to use. A Polhemus Liberty tracking mechanism (see Figure 2-2 D and Figure 2-3 C) was installed to replace the original tracker. The Polhemus system registered changes of direction relative to a predefined neutral, upright chair position. The tracker was mounted on the upper part of the backrest which can be looked as an upright joystick rod that was deflected into the desired direction with the desired velocity (degree of swivel or deflection).

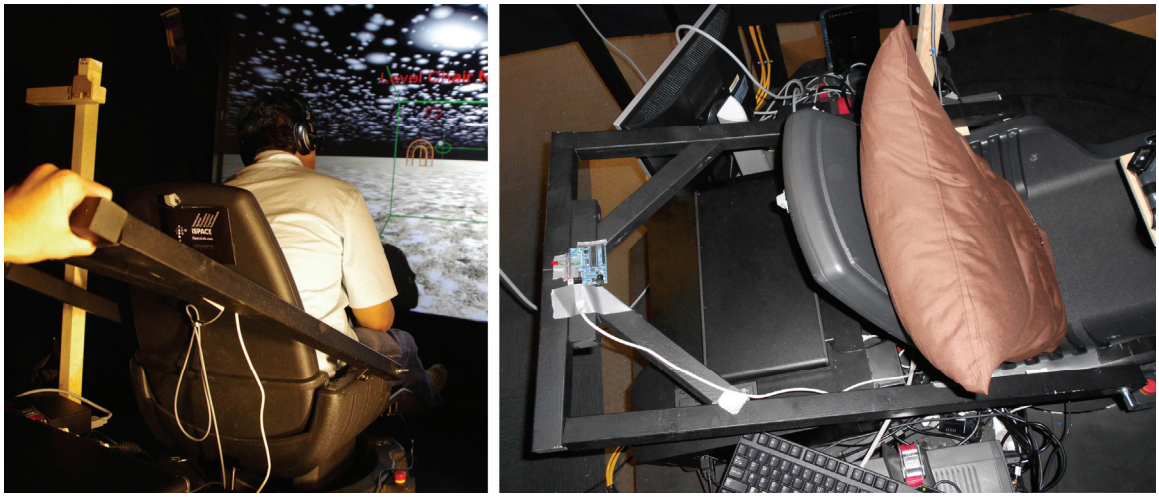

Figure 2-10: Handle to control chair motions from off the chair. Participants remain passively seated in the chair and watch the motion stimulus while being pushed into the direction of VR locomotion.

For the purpose of this experiment, the Gyroxus gaming chair was modified to support additional functionality. The purpose of the modification was to give the experimenter control over the chair motion. Participants remained seated in the chair, but did not apply any forces on the chair themselves. Instead, the experimenter moved the chair with the participant in it using a U-shaped handle, which was added to the original Gyroxus chair (see Figure 2-10). The overall design was much like that of a baby-stroller, except with a tilting seat. The experimenter applied forward/backward and left/right motion to the chair thus forcing it into the desired direction. As such, participants were merely pushed around, passively experiencing physical and the resulting visual motion cues on the screen. In order to alert the experimenter of upcoming conditions

and to prepare for moving the chair, a simple signaling device (see Figure 2-11 A) was used.

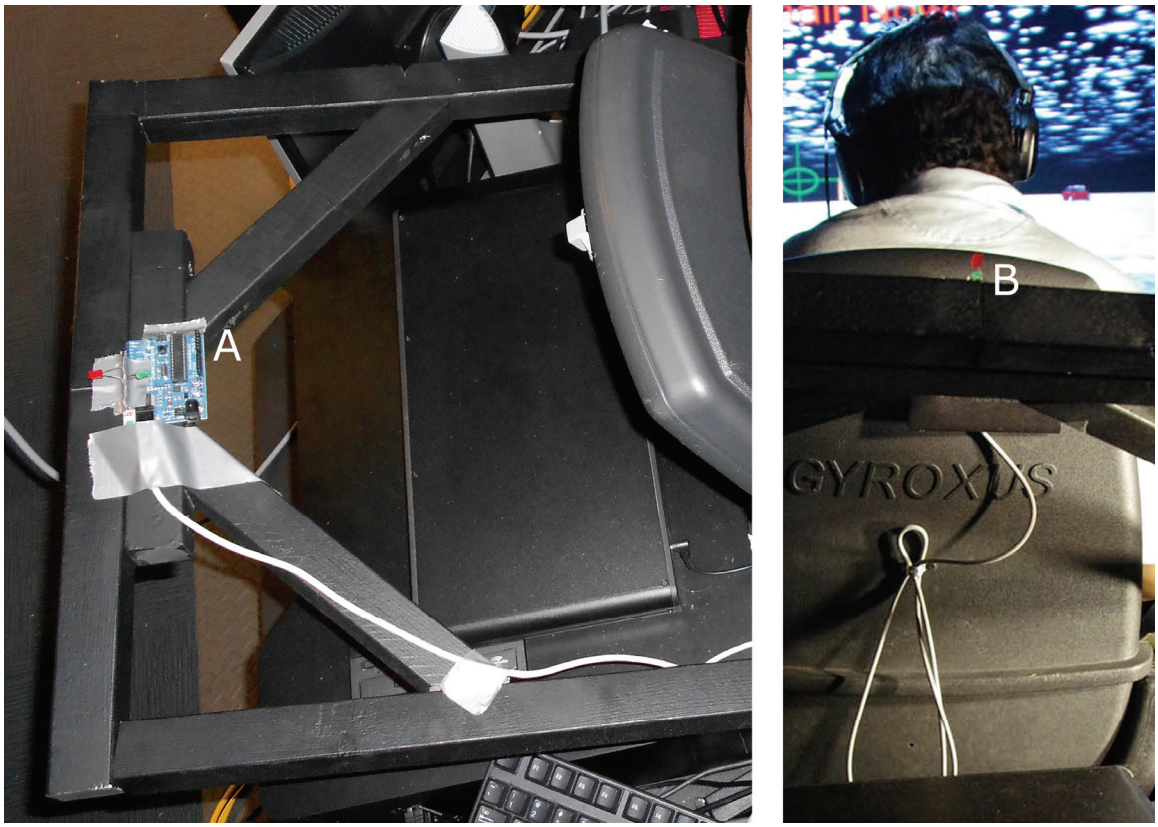

Figure 2-11: (A) Arduino controller that activated indicator lights to alert the experimenter of conditions and various system states. (B) Indicator lights as seen from the view of the experimenter.

Aside from the Gyroxus gaming chair, participants used a joystick to navigate through the virtual world. They did so while being seated in the chair although the chair was mechanically blocked in order to prevent it from moving. Participants placed their index finger on top of the 13cm rod mounted on the joystick and deflected it into desired direction; see Figure 2-12 below. The resulting finger motion was much like pointing into the direction of motion. This pointing action turned out to be more natural and precise than using the original lever. Participants also used the joystick to advance trials and conditions by pressing any button on the joystick. This user intervention allowed them to take a short break between trials to adjust the headgear and take a short rest.

The joystick was mounted on a wooden plate in place of the original Gyroxus game-pad (see Figure 2-12 below). The mounting plate served the purpose of holding the joystick and to provide a parallel mounting surface for a level that moved with the seating platform. Before each day of experiments, the level was used to ensure that the chair is in an upright position to calibrate the tracking system. The wooden plate was also used by participants as leverage for precisely controlling small movements. Instead of leaning, they relied on forces they applied on the plate.

Figure 2-12: Left: Joystick and level gauge (orange device) mounted on the Gyroxus. Right: Top-down view on the Joystick, similarly as to what the participant would see while seated looking down on the joystick. Note the black buttons on the joystick base.

2.2.4. Simulation backend and data acquisition

The simulator base was a custom made motion platform with a rotating module on top of it mounted on the center hub (see Figure 2-13). However, the motion platform was not used in this series of experiments (for further details on the setup, please visit www.ispacelab.com/iSpaceMecha). The module hosted all necessary equipment except the tracker source and projection system. A standard desktop PC was used to generate auditory and visual cues and to guide the procedure of the experiments for additional reduction of user errors. The computer ran customized Python scripts from within WorldViz Vizard, an established and commonly used VR software toolkit which provided built-in support for all the peripherals used in this study, stereo rendering and dynamic view frustrum, although the latter had to be revised to suit our needs.

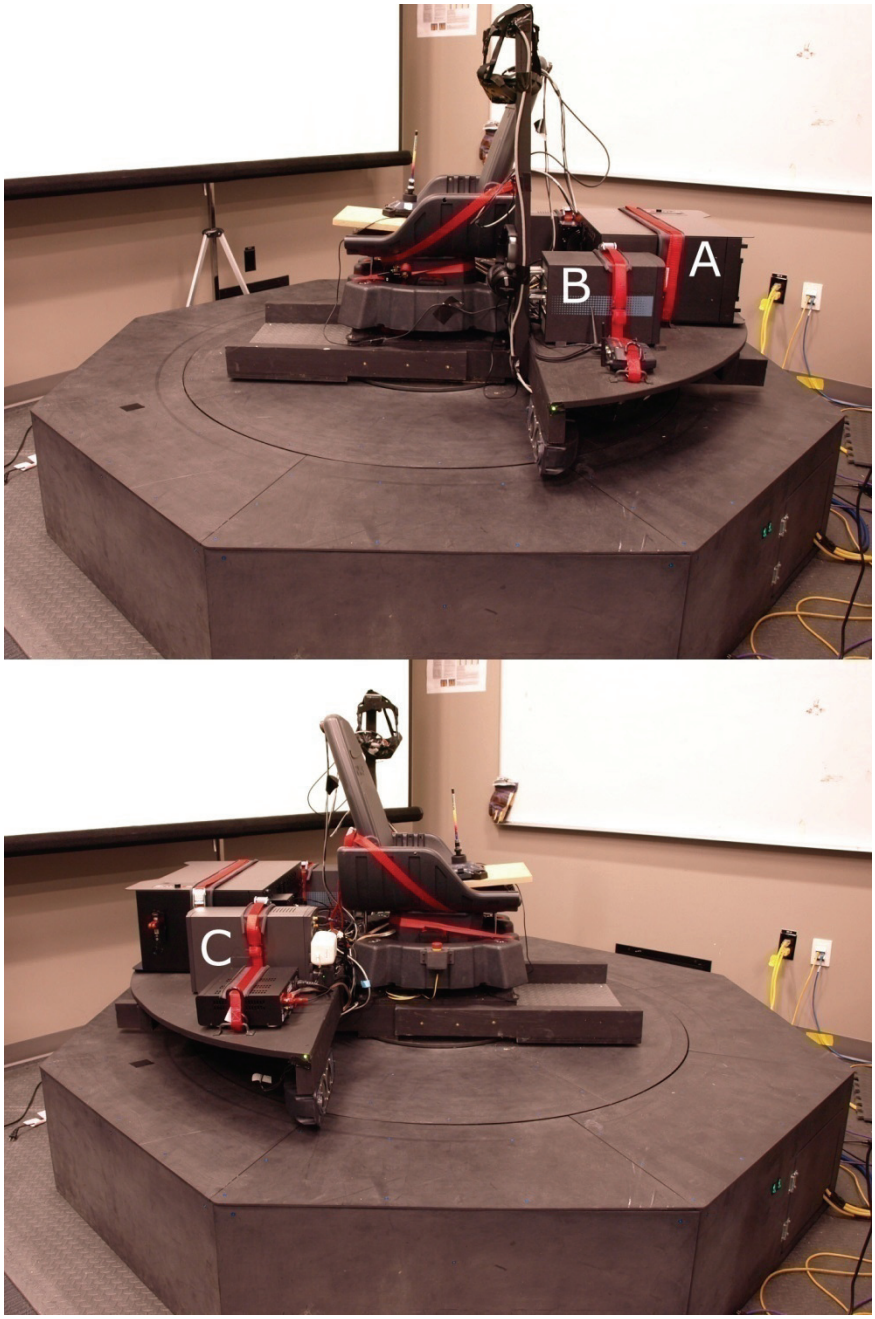

Figure 2-13: (A) Standard x86 based PC (B) Polhemus Liberty base unit. (C) Powerline conditioner and uninterruptible power supply for all components except the projection system.

Except for information collected during the debriefing session (see 2.3.6), all data was collected during the experiment phases and directly recorded into simple, comma-separated text files as a function of the simulation system. For each Participant, a data file was created in which the computer recorded information about the current

experiment phase, condition, values of vection latency, intensity and occurrence. Trajectories of participant locomotion were recorded in separate text files to create plots (such as Figure 2-5) that helped us to evaluate the ability of each participant to follow the follow-me object.

2.3. Procedure and Tasks

2.3.1. Consent and instructions

Shortly after participants arrived, they received a written informed consent and instruction form (see Appendix A) that informed them about procedures, risks, payment and guidelines that governed this experiment (note: institution ethics approval can be found in Appendix B). A general purpose statement of the study was made so that participants were able to put the work into a broader context. Ample time for reading and questions was provided to them to ensure they were informed before they gave their written consent. Refreshments in form of soda and candy were provided to them to ease possible effects of motion sickness caused by the equipment used in this study.

2.3.2. Screening phase

2.3.2.1. Screening for motion sickness

We asked participants before the experiments if they had occurrences of motion sickness in the past and under which circumstances and how intense they experienced these effects. If participants reported past occurrences of motion sickness, we excused them from the study and thus dropped them from the sample. This practice has proven beneficial because participants subject to motion sickness during daily activities get usually sick during the simulation as well.

2.3.2.2. Romberg Test for vestibular dysfunction

In this study, self-motion illusions were based on visual and, to some extent, vestibular cues. It was deemed necessary to screen for proper vestibular function using the Romberg test (Khasnis & Gokula, 2003). Vestibular cues strongly facilitate self-motion perception during real-world locomotion. However, during this series of experiments, participants were “tricked” into believing that they moved, when in fact,

they were not. Thus, an impaired vestibular system could have affected the degree to which participants relied on visual for motion information (lack of vestibular conflict cues) which in turn, could have affected perception of vection and the physical motion cueing used in this experiment.

The Romberg test was conducted with the help of a one meter long strip of silver Ducktape on the lab floor. Participants were then asked to stand on it heel-to-toe so that their feet form a straight line along the tape below them. Participants were then asked to assume a t-pose and to close their eyes. While participants remained in this state, the experimenter counted 30 seconds and then instructed participants to switch feet. Again, the experimenter counted 30 seconds and repeated the whole procedure from the top. If participants maintained their balance, their vestibular system was deemed sufficiently healthy.

2.3.2.3. Establishing a baseline, screening for vection and motion sickness

The purpose of the following pre-experimental screening phase was threefold: Firstly, we wanted to get a conservative estimate on how well participants did within the VE for extreme motion stimuli and prolonged exposure thereof. That is, we wanted to make sure, that participants were enduring enough to withstand a one hour session within the VE without getting sick.

Secondly, we tested participants for susceptibility to vection. If, for whatever reason, participants did not reliably perceive vection within a reasonable amount of time (less than 30 seconds), we had to drop them from the sample as they were unsuitable for the experimental procedure that followed.

Thirdly, we established a baseline for vection intensity based on which participants judged all following trials. This procedure allowed for comparative subjective scaling of the chosen vection metric and is quite commonly used in vection research (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990). Before the vection demonstration we thus instructed participants to assign the 100% mark to whatever vection experience they had after the vection demonstration for the vection intensity ratings and to scale all vection experiences during the following experiments

accordingly. To create this baseline experience, we used the most intense motion stimuli that we possibly could in consideration of user safety and well-being.

The screening phase procedure was as follows: once participants completed the Romberg test, they were seated on the Gyroxus gaming chair and familiarized themselves with the equipment such as the chair, the headgear and interface devices. Participants were then instructed to report vection as soon as they felt like moving. We strongly pointed out that they had to report any effects of motion sickness as soon as they felt them.

The experimenter pressed a button on his keyboard to set the system into the ready state which was in turn signaling the participant (a double beep through the headphones) to start the session with a joystick button. Once the participant pressed any joystick button, the screen faded from black to the visual scene which depicted the trajectory guidance objects within the optic flow field. Along with the scene, the auditory masking sound was presented through the headphones to the participant. After a couple of seconds, the cube accelerated and the experimenter steered the chair along with the participant in it. Two consecutive trials of 1728 degrees curvilinear trajectory with travel speeds of 24 degrees per second were presented. It took 82 seconds to complete each trajectory. Shortly after motion onset, participants verbally reported vection onset. Once the cube stopped moving, an end-of-trial notification sound was presented to the participant and the screen faded to black. We then shortly asked participants about their experience and continued with the next trial. The procedure repeated again in the same manner for the second trial.

2.3.3. Demonstration of the setup

As a prerequisite for all participants, everybody was required to know how to use the VR setup properly. Particularly using the chair to control self-motion through the virtual world as well as the follow-me task was a novelty for all participants. We thus implemented a demonstration phase during which the experimenter himself sat on the chair and demonstrated the required tasks to the participant. For this demonstration phase, we used two randomly selected consecutive trials, one with a turn velocity of 8°/s, the other of 24°/s degrees per second. The procedure was identical to the

screening phase mentioned in 2.3.2.3 above. In a dialog with the participant, ample opportunity for questions and answers was provided. Once the procedure was well understood, participants were allowed to continue and participate in experiment 1.

2.3.4. Experiment 1: Training

The purpose of experiment 1 was primarily to reduce variability in the response of participants due to learning effects, perceptuomotor adaption to the VR and the novelty of experiencing vection. Additionally, experiment 1 gave us a preliminary idea about our initial hypotheses. It was thus important to utilize exactly the same procedure and conditions of experiment 2. As mentioned in 2.2.1.2, we dropped the straight path (0º/s turn velocity) condition because we assumed that 1) participants get better training out of practicing curved versus straight paths and 2) vection may be more enhanced for curved than straight paths in context of the vection literature (Trutoiu et al., 2009). Eliminating the straight path condition overall saved time and thus unnecessary exposure of participants to the VR. As a result, experiment 1 contained only 8 trials in total. Participants thus had four motion conditions with **two trials** each (**8º/s and 24 º/s**, random **turn** direction) ahead of them. All these conditions were blocked following the blocking schema mentioned in 2.4.3.1.

For the **passive no motion cueing condition**, participants just sat in the Gyroxus chair and watched a pre-recorded animation on the screen where the view was automatically following the cube. The view was animated using the same trajectory parameters of the follow-me object, just offset by two seconds. Thus, participants were exposed to the ideal path trajectory, as actively controlling the navigation (as for the last two conditions mentioned below) typically resulted in slight deviations from the predefined path.

For the **passive motion cueing condition**, participants also just sat in the chair and watched the visual motion, but the experimenter controlled the locomotion on the screen by moving the chair and thus the participant within it. This condition is identical to the vection demonstration/screening phase mentioned in 2.3.2.3. For this condition it was important, that the experimenter was 1) well trained to approximate the predefined path by following the cube using the handlebar and 2) ready and waiting to take control

at the beginning of each trial. To prepare the experimenter, a few seconds before this particular condition, a blinking red light (see Figure 2-11) signaled an upcoming, passive motion cueing condition.

In the **active no motion cueing condition**, participants sat still in the chair, but used the joystick to control the locomotion through the virtual world.

Finally, during the **active motion cueing condition**, participants used the Gyroxus gaming chair to control locomotion through the virtual world by physically leaning.

For both active conditions, the approximation of the predefined trajectory as a result of following the follow-me object was dependent on participants skill of using the chair or joystick. To acquire these skills, participants underwent a training phase before an upcoming active block. Participants had to navigate a complex and challenging training parcours and successfully pass in order to continue. They were required to use the interface device of the upcoming block to closely follow the green cube along trajectories of random curvature radii and straight path lengths. If the participant failed to maintain a proper lock on the cube, the training phase was repeated until the participant was able to follow the cube sufficiently well based on the judgment of the experimenter. At the end of each training trial, the computer prompted the experimenter to continue to the experiment block or repeat the training.

Once participants were sufficiently skilled at using the chair or joystick, the experimenter pressed a button on the keyboard to move on to the experiment phase. Once before the first trial of each block, the computer verbally notified participants about the upcoming condition, that is, using the chair or joystick to navigate, being pushed in the chair or just watching the scene. A double beep followed which indicated to the participant that the system was ready and waiting to continue. The participant then pressed a button on the joystick and the trial started. Again, the scene was faded in from the black, default screen and at the same time, the masking noise started. After a couple of seconds, the cube began to move and participants engaged in the task that the current condition called for. The participant then verbally announced as soon as they experienced vection, in a manner such as “now” or “I’m moving”, etc. The experimenter

then quickly pressed the space bar on a keyboard to record the **vection latency**. The trial continued until the cube came to a full stop and the participant navigated within 5 meters behind it. A notification sound played which indicated that the trial is completed. The screen faded back to black and the masking sound stopped.

A text input dialog opened up on the screen and the experimenter asked the participant about the **vection intensity** of the previous trial. The participant then answered and the experimenter entered the response value into the text dialog. The participant was able to verify the entered value and the value was then confirmed by pressing Enter. The dialog disappeared and the system signaled the participant that it is ready to continue to next trial.

Once one block was completed (every 2 trials), the system instructed participants to take a short break. Ambient light was then raised and most participants removed the headgear to rest a few seconds. The experimenter took the break as an opportunity to ask participants about how they felt. Some participants noted dizziness and eyestrain, so we waited until they felt ready to proceed again. After all blocks were completed, the computer announced the beginning of experiment 2.

2.3.5. Experiment 2: Main experiment

By this point, participants were very well trained and accustomed to the virtual reality apparatus and tasks. All participants were now at a baseline level from which we started our main investigation.

Experiment 2 was in its procedure identical to the previous experiment. Instead of two trajectories per condition, six trajectories were included as we added a straight path trajectory **(0º/s**) and **both turn directions** (left/right) for each of the two turns (**8º/s and 24º/s**). Note: **two identical straight path conditions** were included in balance to the two turn directions to achieve a complete dataset. Even though straight path conditions were somewhat novel to participants, we assumed that they had no trouble navigating on a straight path in light of their curved path performance. Additionally, participants experienced some straight path segments during the training parcours in experiment 1, so that they were reasonably well prepared for all conditions in this experiment.

After the last block of experiment 2, the computer announced the end of the study and notified the experimenter though a light on the chair that the study is now completed. The screen remained black and the experimenter raised the lights and helped participants to remove the headgear and step off the simulator. After a short break and refreshments, the experimenter sat down with the participants for a brief post-experiment interview.

Overall, it took about 32 seconds per trial and after each trial, participants took about 10 seconds to provide a rating of vection intensity. Between each condition or block, a short 2 minute break was put in place to reduce fatigue and occurrence of motion sickness. As a result, participants spent about 14 minutes on experiment 1 and were exposed to the motion stimulus for about 4.5 minutes (excluding screening, demonstration and training). Participants spent about 25 minutes during experiment 2 and about 13 minutes of that time, they were exposed to the motion stimulus.

2.3.6. Debriefing and observations

The debriefing phase took place directly after the VR study and served two purposes. Primarily, we used this time to gather additional information about participants and their experiences in the VR that we did not capture during the experiments. The secondary purpose of this debriefing phase was to allow some time for participants to re-adapt to the real world under supervision. Some participants reported dizziness which disappeared during the interview, others utilized the bathroom before the interview to freshen up. No severe gastric reactions were reported and motion sickness effects consisted mainly of eyestrain, slight dizziness, mild headache and queasiness.

The questions participants were asked during the interview were ordered by themes and presented in the following order:

Demographics: age, gender, occupation or topic of study.

Prior gaming experience: “Do you play 3D computer games?”, “How many hours a day do you play computer games?”

Vection intensity: “How would you overall rate vection intensity for the condition in which you 1) just watched the scene, 2) used the joystick, 3) were being pushed in the chair and 4) used the chair?” Participants reported on a scale from 0-100%.

Vection intensity as a function of straight vs. curved paths: “Was vection overall stronger/similar/weaker for curved paths as compared to straight ones?”, “By how much was it stronger?” Participants reported the type of paths and provided a number on a scale from 0-100%.

Joystick and chair usability: “How intuitive was the chair to control?”, “How intuitive was the joystick to control?”, “How well could you navigate and follow the green cube using the chair?” and “How well could you navigate and follow the green cube using the joystick?”. Participants reported on a scale from 0-100%.

Aside from these quantitative data, we attempted to get a more complete picture about user experiences of controlling locomotion with the joystick and chair. To that end we asked them two open questions that followed in the interview. The first question related to **interface device preference** (“Overall, would you prefer to use the chair or joystick for navigating virtual worlds? Why?”) and the second question related to their **opinion of the motion cueing paradigm** used in the experiments (“What did you think of the physical motion used in the study (controlling the chair/being pushed) and what was the best/worst about it?”).

2.4. Experimental design

2.4.1. Experiment 1: Training

During experiment 1, 24 participants performed 8 trials for a factorial combination of 2 interaction conditions (active/passive), 2 motion cueing conditions (motion/no motion cueing), and 2 turn velocity conditions (8º/s and 24º/s). Turn direction (left/right) was randomized for each turn velocity condition and the order of conditions was fully balanced across participants. A fully crossed within subjects design with restricted randomization and hierarchical blocking (2 level split-plot design, split (interactivity), split (motion) plot) was used.

2.4.2. Experiment 2: Main experiment

During the main experiment the same 24 participants performed 24 trials as a result of a factorial combination of 2 interaction conditions (active/passive), 2 motion cueing conditions (motion/no motion cueing), 3 turn velocity conditions (0°, 8° and 24°/s) and 2 turn directions (left/right). Because straight path trajectories do not have turn directions, participants were presented with two straight path trials in lieu of left and right turns to ensure a complete data set. A fully crossed within subjects design with hierarchical blocking (2 level split-plot design, split (interactivity), split (motion) plot) was used. Besides the amount of presented turn velocities and restricted turn direction randomization, the procedure of experiment 2 was identical to experiment 1 and was run directly after experiment 1 in the same session.

2.4.3. Independent parameters

2.4.3.1. Conditions and blocks: Interactivity and motion cueing

We investigated the relative contributions of ***interaction*** and ***motion cueing*** on visually induced vection along curved (8°/s, 24°/s) and straight (0°/s) paths. The combination of interaction and motion cueing we used in both experiments is depicted in the 2x2 condition matrix in Table 2-2 below.

Conditions	**Motion cueing** (moving participant)	**No motion cueing** (only visual motion is provided, stationary participant)
Active (participants control motion)	Chair: active motion cueing (participant moves the chair)	Joystick motion control (participants uses the joystick)
Passive (participants don't control motion)	Chair: passive motion cueing (experimenter moves the chair)	Stationary observing (still participants watch the scene)

Table 2-2: User interaction and motion cueing conditions for both, experiment 1 and experiment 2.

Participants were not presented with a fully random order of all possible trials because our setup did not support quick changes between conditions. For example, going from an active motion cueing trial to an active no motion cueing trial required the experimenter to manually install a mechanical linkage on the chair to prevent it from accidentally moving when participants used the joystick (otherwise motion cues could have affected a no motion condition). Because of this overhead we clustered all trials of each block into a sequence. Because trials were not presented in a fully randomized fashion, counterbalancing and different statistical approaches were necessary.

A counterbalancing scheme was used in an attempt to minimize carryover effects. A 2 level split-plot by interaction (active/passive) and motion condition (motion/no motion) was used. That is, we first blocked all conditions of interactivity and then, for each level of interactivity, we blocked motion cueing. A different blocking scheme was used for each experiment. It took 8 participants to complete the full blocking scheme and we iterated three times in total over the scheme.

Due to random ordering of trials within blocks, any carryover effects were spread equally onto other treatments and therefore mitigated. Additionally, we used a short break and a blacked-out screen in between trials to further limit carryover effects from the previous trial as well as fatigue and motion sickness.

We thus excluded carryover effects from the statistical model. Training and fatigue effects were included into our statistical model as a single period factor. We used period factors to track changes in responses as they occurred over time, beginning from the first to the last trial. However, this approach by itself would not disambiguate between training or fatigue effects and only looks at overall changes in participant behavior for each experiment separately.

2.4.3.2. Turn velocity and turn direction (trajectories)

For each block, participants were presented with trajectories of various curvature and turn direction. For experiment 1, each combination of interactivity and motion cueing was assigned a set of two paths, one with a 8°/s and the other with a 24°/s turn velocity in random directions. In experiment 2, for each of such combinations, a set of six paths were presented with 0°/s, 8°/s and 24°/s turns. For each turn condition, two trials were

presented in either left or right direction except for the straight path where two straight path segments were presented.

As in line with Trutoiu et al. (2009), we did not find an effect of turn direction and thus opted to simplify our analysis by excluding turn direction from our model. The main reason for doing so was the inclusion of a 0°/s level in experiment 2 which yielded three turn conditions: left, right, and straight. The straight level is completely confounded with the 0°/s level, which would make untangling the separate effects of velocity and angle highly complicated, but not impossible.

2.4.4. Dependent measures

2.4.4.1. Vection intensity

Vection intensity [0-100%] was defined as the experienced magnitude of self-motion estimated relative to previous vection experiences during the vection demonstration/screening phase in which participants were exposed to intense motion stimuli not replicated later on in the experiments. This upper limit marked 100% vection intensity whereas 0% marked no perceived self-motion at all. Participants verbally reported this estimate after each trial. We treated vection intensity as a continuous response within a linear mixed model analysis.

2.4.4.2. Vection latency

Vection latency [0-32s] was defined as the time between the onset of the visual motion stimulus and a button press participants applied to the joystick in the moment they perceived vection. The 32 second upper limit was equal to the duration of the trial. All participants were screened for vection susceptibility and we assumed, that all participants would eventually perceive vection in all trials. However, trials were limited to a duration of 32 seconds each due to time constraints and participants were not always able to perceive vection during the time allotted in some trials. In case the trigger was not activated, we populated the data field with a default value of 32 seconds, the duration of the trial.

For instances where the system recorded 32 seconds, we were faced with three possible situations: 1) If participants also reported 0% vection intensity for the same trial,

they did not perceive vection and more time would have been necessary to elicit vection in them, 2) They perceived vection (vection intensity > 0%), but failed to activate the trigger to inform the system that they did experienced vection or 3) They experienced vection late (vection intensity > 0%) and used the trigger, but did so at end of the trial where triggers were not recorded anymore.

Unfortunately, we cannot disambiguate between the latter two issues nor extract useful latency information from them with the measures we have and thus decided to drop those cases from our analysis. The total occurrences of these situations were less than 5% in both experiments so that this procedure should not have introduced a significant bias. We thus modeled vection latency under normality assumptions using a linear mixed model.

2.4.4.3. Occurrence of vection

The occurrence of vection measure reflected whether or not participants perceived vection for any given trial. If participants reported 0% vection intensity and vection latency of 32 seconds, then they did not experience vection in the scope of our analysis. If participants reported vection intensity greater than 0% regardless of vection latency, then we assumed he perceived vection during the trial. If participants thus rated vection intensity, we interpreted it as if they perceived vection at some point during the trial. It remained unclear tough, when this event exactly occurred.

For experiment 1, about 7% and for experiment 2, about 10% of trials with no vection were recorded. The binomial nature of this measure would normally call for a logistic regression analysis, but due to the few instances of failed vection, we were faced with zeros in most treatment combinations and a logistic regression model would have failed. We thus opted to drop the normality assumptions in favor of error terms and treated the data as a numerical response. We were then able to model the data within a linear mixed model which can outperform logistic regression. This approach is commonly used especially in cases like these (Fang & Loughin, 2012).

2.4.5. Post-experiment interview data

2.4.5.1. Overall vection intensity

In a post-experimental questionnaire (see 2.3.6), participants rated their overall experience of vection intensity for each one of the four conditions using the same rating standards as in the experiments. Thus, each participant reported four vection intensity ratings between 0% and 100%. The four groups were then compared using a 2x2 factorial structure in a randomized complete block design, with "action" (active/passive) and "motion" (motion/no motion) as the factors and levels. Data of this post-experimental measure are summarized in section 3.3 and 3.4.

2.4.5.2. Perceived usability of joystick and chair

Participants rated the overall usability of the two input devices joystick and chair during a debriefing interview (see subsection 2.3.6) after both experiments had finished. We asked two questions about participants' ability to locomote within the virtual environment using the two interfaces. An **Intuitiveness** measure was used to indicate how natural and easy it was to use the interface without extensive training. A **precision** measure was used to indicate what level of control they had over the entire range of motion, from large to very slight applications of motions on the interface. For both measures, participants responded on a scale between 0% and 100% where 0% marked lowest (not intuitive/imprecise) and 100% highest (most intuitive and precise). We used these measures to corroborate the vection data collected during the experiments, although no statistical correlation was executed.

2.4.5.3. Novices versus "Gamers"

To understand how usability of both interfaces was affected by prior gaming experience, we added a 3D gaming experience measure into the questionnaire (see 2.3.6). If participants played 3D games more than one hour per day, they were considered "gamers" in the context of this study. We tested for a difference between "novice" and "gamer" groups using a t-test.

2.4.5.4. User preference of joystick vs. chair

We were interested how observers actually felt about using the two interfaces to understand if the chair may be a substitute for the joystick. We asked them, which

device they preferred and why. Responses were simply counted for each category (joystick/chair) and briefly summarized.

2.4.5.5. User opinions of physical motion cueing

We asked participants about their opinion of the motion cueing used in the experiments and how it should be improved. We informally looked at the collected responses with the goal to make better informed choices for future VR implementations. We looked recurring patterns and created category for each type of pattern. Categories and the frequency of responses that fell within each category were plotted to aid in detecting benefits and issues commonly associated motion cueing (use of the chair).

2.4.5.6. Perceived difference between curved and straight paths

We asked participants if they felt a difference in strength of vection between curved and straight paths. They were instructed to mention if curved and straight paths were perceived differently or not and if so, which type yielded the strongest sensations of vection. We used this information to help us corroborate our findings from the main experiments.

2.4.6. Response bias

Participants were told that the findings of this research were used to improve the user experience within computer mediated environments and to learn more about how humans perceive their surrounds. No specifics were disclosed to reduce response bias. Interactions between participants and experimenter were kept at a minimum. The experiment was standardized using computer system that dictated the procedure of the treatment phases based on a pre-programmed script. Instructions during treatment were computerized to further minimize procedural differences between participants. The same experimenter was used to conduct the study for all 24 participants and was the only person present during experiments aside from the participant. The experimenter was very familiar with the procedure, this particular setup and well trained to handle it.

3. Results and discussion

A 3-way within-subjects ANOVA with a covariate (period) was used to analyze our data; specifically, a split-split-plot within-subjects design with turn velocity (experiment 1: 8º/s, 24º/s; experiment 2: 0º/s, 8º/s, 24º/s), motion cueing (no motion cueing, motion cueing) and interactivity (active, passive) as factors and vection intensity, latency and occurrence as dependent variables was used to account for the blocking method in our experiment. For each experiment, a time period factor (covariate) was included in the model to account for effects that vary systematically over the course of the experiment for each individual. According to the blocking model, time period was split in two halves for levels of interactivity which were then split in two halves for levels of motion cueing condition and each of these quarters were then again split into increments of turning condition. These last increments were the periods that we accounted for in the analysis. The periods were treated as categorical data.

The main and interaction effects are summarized in separate subsections for each experiment; see 3.1 below. Detailed analyses of main and interaction effects are provided in separate subsections for each factor, see 3.2 - 3.4. Joystick and chair usability and vection data are summarized in detail in subsection 3.5. We chose to contextualize our post-hoc analyses with our data plots for better readability and understanding. Thus, data plots appear in conjunction with post-hoc analyses for each factor instead of presenting post-hoc analyses in a separate subsection. Unless otherwise noted, Least Square (LS) means (or marginal means) were reported in our data summary. LS means are adjusted for variances of other factors in the model and are thus a better estimate of the true population mean compared to the standard arithmetic mean in the context of our design. When standard arithmetic means are used, the term *mean* is mentioned in the expression. Differences between means are signed. Negative differences of means are the result of subtracting means of condition *a* minus condition *b* where condition *a* < condition *b*. Positive values thus indicate a decrease from condition a to condition b.

3.1. F-test summaries

3.1.1. F-test summary for experiment 1 (training)

An *F*-test summary of the vection data for experiment 1 is shown in Table 3-1 below. This period effect was not calculated for the vection occurrence measure due to the limited instances of non-vection. It was impossible to distinguish between period effects and effects of other experimental variables. We were assuming, therefore, that the period effects are of no or lesser importance than other experimental variables.

	Vection Intensity			Vection Latency			Vection Occurrence		
Effect	DF	F Value	Pr > F	DF	F Value	Pr > F	DF	F Value	Pr > F
Interactivity	F(1,23)	1.54	0.228	F(1,20.8)	9.74	**0.005****	F(1,24)	5.27	**0.031***
Motion cueing	F(1,46)	15.53	**0.0003*****	F(1,41.3)	0.48	0.492	F(1,48)	1.59	0.214
Interactivity x Motion cueing	F(1,46)	0.22	0.644	F(1,41.4)	1.97	0.168	F(1,48)	0	1.00
Turn velocity	F(1,92)	23.39	**<0.0001*****	F(1,75.3)	0.95	0.333	F(1,96)	4.97	**0.028***
Interactivity x Turn velocity	F(1,92)	0.01	0.923	F(1,76.8)	0.05	0.818	F(1,96)	4.97	**0.028***
Motion cueing x Turn velocity	F(1,92)	2.49	0.118	F(1,75.5)	0.33	0.565	F(1,96)	2.21	0.141
Interactivity x Motion cueing x Turn velocity	F(1,92)	0.53	0.467	F(1,76.7)	0.03	0.854	F(1,96)	2.21	0.141
Period	F(7,108)	0.18	0.989	F(7,89.7)	0.45	0.871			

Table 3-1: F-test results. Significant effects are typeset as bold; * p<.05, ** p<.01, *** p<.001.

3.1.2. F-test summary for experiment 2 (main experiment)

An *F*-test summary of the vection data for experiment 2 is shown in Table 3-2 below. As for experiment 1, a period effect for the vection occurrence measure was not calculated.

	Vection Intensity			Vection Latency			Vection Occurrence		
Effect	DF	F Value	Pr > F	DF	F Value	Pr > F	DF	F Value	Pr > F
Interactivity	F(1,22)	0.29	0.594	F(1,20)	7.58	**0.012***	F(1,23)	1.5	0.233
Motion cueing	F(1,44)	17.31	**0.0001*****	F(1,35.8)	0.37	0.549	F(1,46)	0.09	0.769
Interactivity x Motion cueing	F(1,44)	0	0.965	F1(35.7)	0.05	0.827	F(1,46)	0.09	0.769
Turn velocity	F(2,452)	83.75	**<0.0001*****	F(2,393)	14.99	**<0.0001*****	F(2,184)	8.14	**0.0004*****
Interactivity x Turn velocity	F(2,452)	1.02	0.360	F(2,395)	0.08	0.920	F(2,184)	0.8	0.450
Motion cueing x Turn velocity	F(2,452)	0.04	0.960	F(2,396)	1.36	0.258	F(2,184)	0.3	0.745
Interactivity x Motion cueing x Turn velocity	F(2,452)	1.03	0.358	F(2,396)	0.06	0.940	F(2,184)	0.04	0.959
Period	F(23,431)	0.6	0.932	F(23,377)	0.66	0.880			

Table 3-2: F-test results. Significant effects are typeset as bold; * p<.05, ** p<.01, *** p<.001.

3.2. Turn velocity

In the context of the vection literature, direct comparisons between turns and straight path conditions are scarce, which makes a statements about the effects of turn velocity on vection difficult as experiments that either investigate linear or curvilinear vection can greatly differ in their approaches. Trutoiu et al. (2009) conducted a series of studies that investigated effects of turn velocity on vection for highly naturalistic and abstract motion stimuli. We re-visited their study in the context of current, affordable 3D gaming and VR setups to confirm, if simply changing visual trajectories can be beneficial to vection. We hypothesized that increasing turn velocity increases vection intensity, reduces vection latency and increases the likelihood of vection occurrence under conditions of optic flow, dynamic perspective renderings and binocular viewing conditions as well (see subsection 1.3.1). If increasing turn velocity enhances vection, existing and new motion simulators may be improved without additional purchase of equipment and associated efforts and cost. The effects of the factor turn velocity on vection in the context of our study are summarized in the subsections below.

3.2.1. Main effects of experiment 1 (before) vs. experiment 2 (after)

In the following section, we directly compared the effect of three turn velocity conditions, specifically straight paths (0°/s), wide turns (8°/s) and narrow turns (24°/s) on the three vection metrics vection intensity, latency and occurrence. We first looked at the relative contribution of turn velocity on vection overall, averaged over conditions of motion cueing and interactivity. In the subsection to follow, we investigated how other factors such as motion cueing and interactivity interacted with effects of turn velocity and to corroborate our quantitative findings, we then summarized our findings from a post-experimental interview.

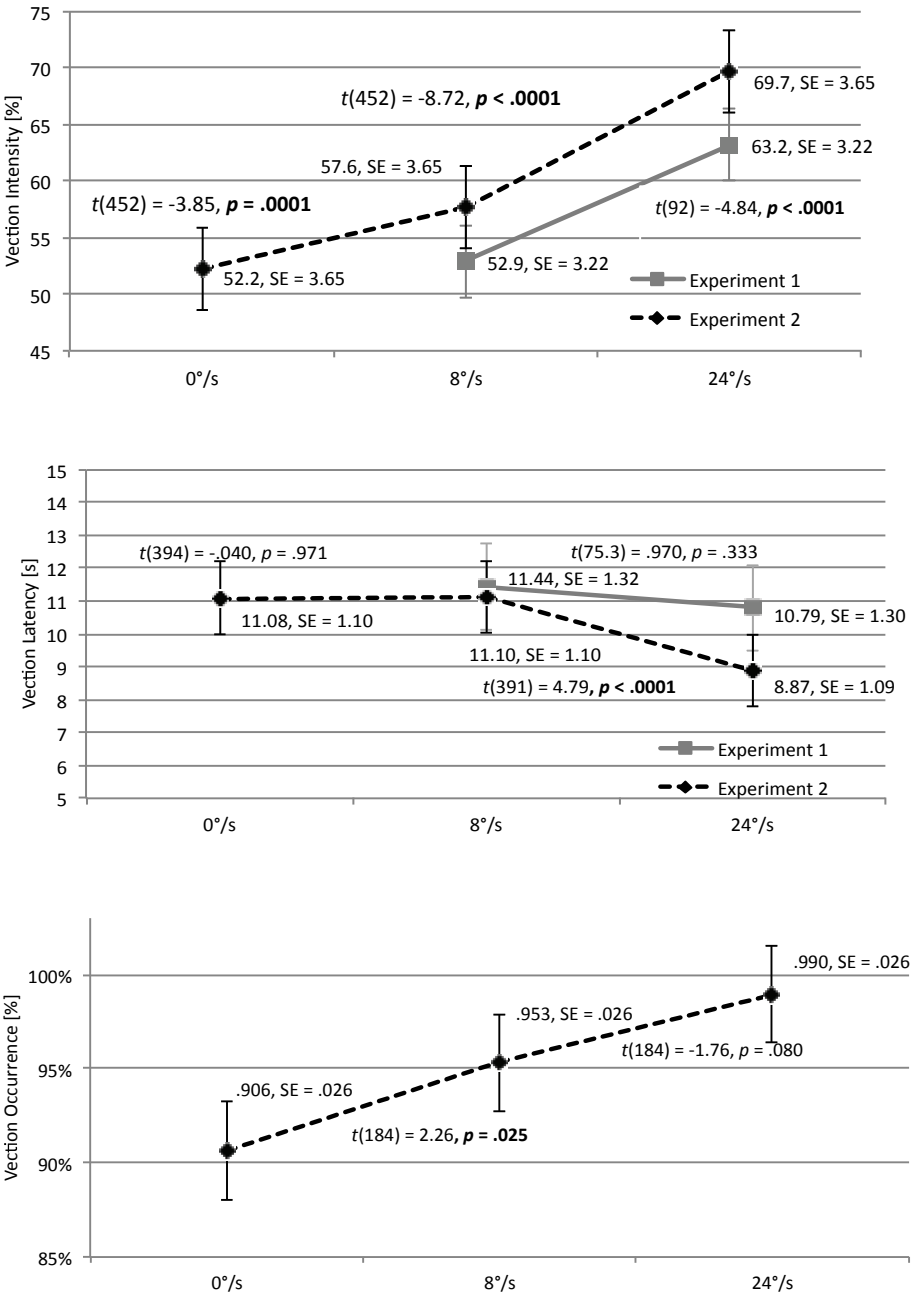

Figure 3-1: Top: Magnitude estimates of vection intensity (%). Middle: Vection latency (s). Bottom: Likelihood of vection occurrences (%).Data points are LS means, whiskers represent the standard error (SE). Comments show data point values and difference statistics. Significant differences are highlighted in bold.

Figure 3-1 above depicts main effects of turn velocity on vection intensity, latency and occurrence in a side-by-side comparison of both experiments. The data presented here are thus averages of interactivity and motion cueing for each turn velocity condition. The main effects plots reveal, that the overall effect of turn velocity on vection remains the same for both experiments.

Specifically, **vection intensity** was consistently higher for greater turn angles with a greater noticeable difference between 8°/s vs. 24°/s than for 0°/s vs. 8°/s. While the trend remained almost identical between the two experiments, participants reported higher vection intensity during experiment 2 compared to experiment 1.Turn velocity significantly affected vection intensity in both, experiment 1 ($F(1,92) = 23.39$, $p < .0001$) as well as experiment 2 ($F(2,452) = 83.75$ $p < .0001$).

Vection latency was somewhat reduced by increasing turn velocity. Even though there was a slight reduction of vection latency from 8°/s to 24°/s noticeable in experiment 1, the effect was not strong enough to be statistically significant, see middle plot in Figure 3-1. In experiment 2, vection latencies were consistently lower than in experiment 1,although no difference was noticeable for smaller differences between turn velocity conditions, such as the straight path (0°/s) and small turns (8°/s). Turn velocity thus did not significantly affect vection latency in experiment 1 ($F(1,75.3) = .950$, $p = .333$), but did so in experiment 2 ($F(2,393) = 14.99$, $p < .0001$).

Vection occurrence was higher for turns compared to straight paths in experiment 2 although we did not notice a difference between small (8°/s) and large (24°/s) turns, see Figure 3-1 (bottom plot). A possible explanation for this effect can be found in a lack of statistical sensitivity as occurrences of no vection was less than 5% in total. Vection occurrence was significantly affected in both, experiment 1 ($F(1,96) = 4.97$, $p = .028$) and experiment 2 ($F(2,184) = 8.14$, $p = .0004$). In summary, both experiments indicate that higher turn velocities enhanced vection across all three vection metrics. Although vection latency was not significantly lowered by higher turn velocities in experiment 1, the slight trend towards lower vection latencies was more pronounced and the effect was statistically significant for experiment 2.

3.2.2. Effects of turn velocity on vection during training (experiment 1)

In the previous subsection, main effects of turn velocity for both experiments were summarized. The purpose of the following two subsections is to disambiguate turn velocity from the factors motion cueing and interactivity to show, how these factors may have affected the overall trends outlined before.

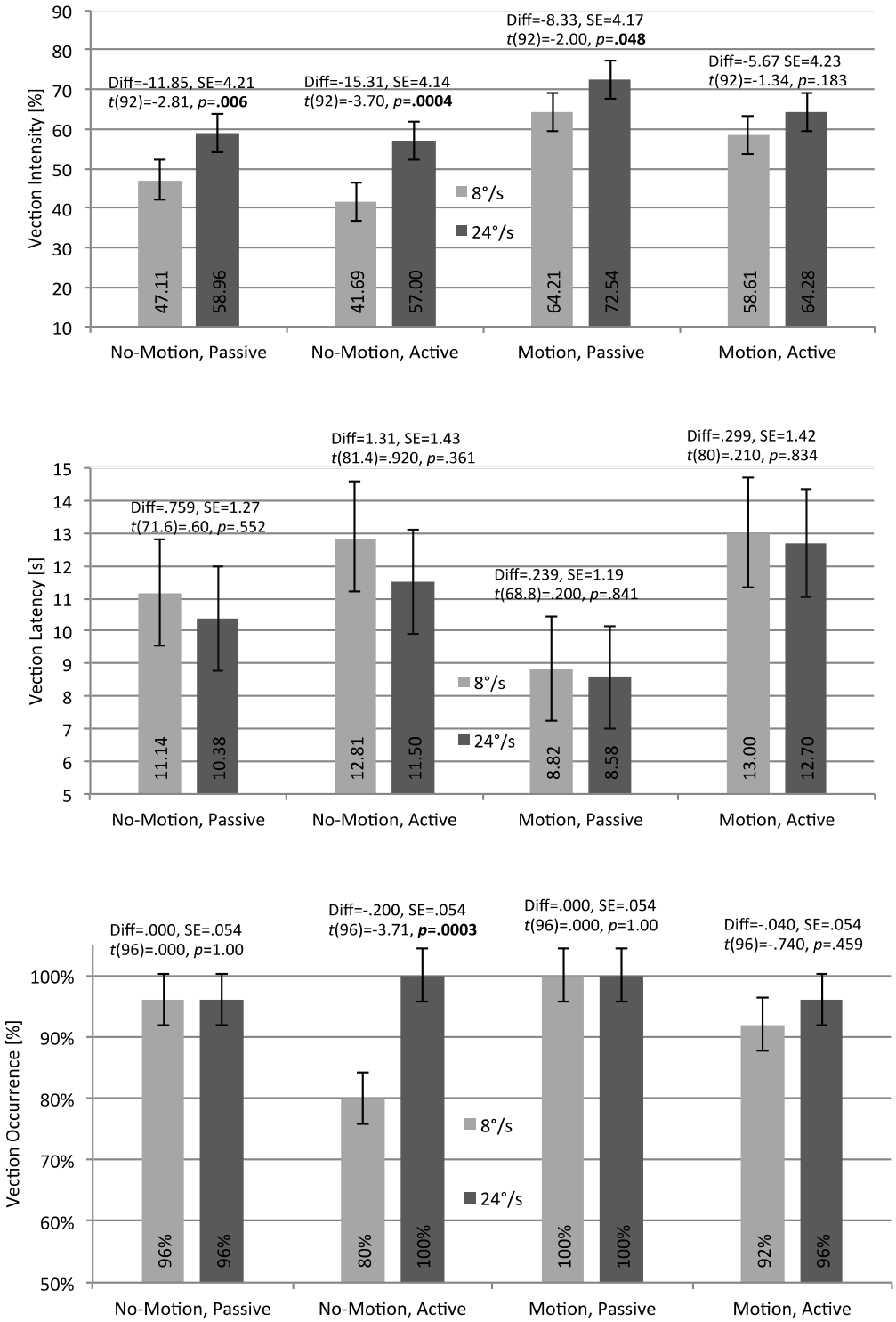

Figure 3-2: Vection intensity (%), latency (s) and likelihood of vection (%). Comments above bars show difference statistics. Plotted are LS means and the standard errors (whiskers). Bold p-values highlight significant differences.

Figure 3-2 above shows three plots, one for each vection measure. Participant responses for each measure are grouped by experiment condition. Relevant statistics are plotted above the bars. Overall, the plots reveal that higher turn velocities generally enhanced vection. Specifically, **vection intensity** was higher for higher turn velocities in all but the active motion condition where participants moved themselves in the chair to control their locomotion. **Vection latency** had a slight tendency to be lower for higher turn velocities although this effect was not statistically significant. Finally, the **occurrence of vection** was more likely for higher turn velocities when participants used the joystick to navigate through the virtual world. Turn velocity did not affect the likelihood to induce vection for the remaining three conditions although a slight improvement of vection likelihood for higher turn velocities is visible for the active motion condition where participants used the chair to locomote through the virtual world. This effect was not statistically significant, however. To summarize, higher turn velocities increased vection intensity responses and the likelihood of vection to occur in participants, but vection latency was not significantly reduced (see F-test summary in subsection **Error! Reference source not found.**).

3.2.3. Effects of turn velocity on vection after training (experiment 2)

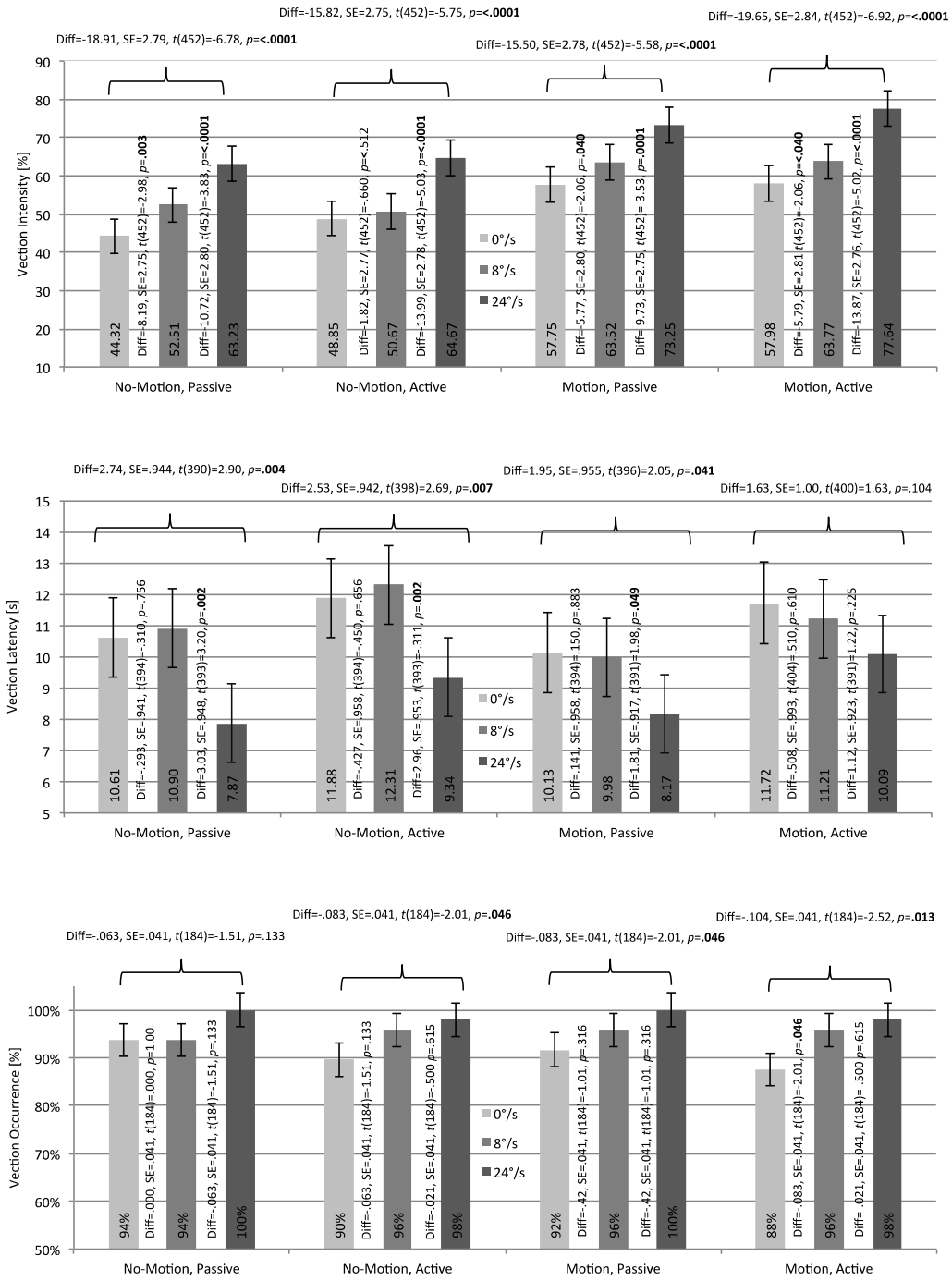

Figure 3-3: Vection intensity (%), latency (s) and likelihood of vection (%). Comments above and between bars show difference statistics. Plotted are LS means and the standard errors (whiskers). Bold p-values highlight significant differences.

Figure 3-3 depicts a summary of the vection data for all three vection metrics of experiment 2. A similar trend as in experiment 1 can be observed in that higher turn velocities generally enhanced vection. **Vection intensity** was higher for higher turn velocities under most conditions. However, in the active, no motion cueing condition where participants used the joystick to navigate through the virtual world, we could not detect an increase of vection intensity between the straight path condition (0°/s) and the small turn (8°/s). Higher turn velocities reduced **vection latencies** in all but the active motion cueing condition where participants used the chair to navigate through the virtual world. We detected an overall increase in **occurrences of vection** for higher turn velocities although this effect was only noticeable when the difference of turn velocity was the greatest, specifically between straight paths and turns at a velocity of 24°/s. However, we could not detect this effect in conditions where participants just sat in the chair and watched prerecorded motions. An exception was the active motion cueing condition where participants used the chair to control their locomotion. In that condition, we noticed an increase in vection occurrence between straight paths (0°/s) and small turns (8°/s). In summary, higher turn velocity significantly enhanced vection for all three vection metrics. Vection intensity and the likelihood of the occurrence of vection was greater whereas vection latency was shorter with increasing turn velocity, see *F*-test summary for experiment 2 in subsection 3.1.2.

3.2.4. Post experiment interview data

In the interview after the experiments, we noticed that participants overall attributed a stronger sense of vection to curvilinear compared to linear trajectories. Twenty one out of our 24 participants (87.5%) stated that curvilinear paths resulted in a more intense sensation of vection, 2 out of 24 (8.5%) participants mentioned that straight paths were experienced as more intense over curved paths and 1 out of 24 (4%) answered that he felt curved paths more intense when moving, but straight paths are more intense under passive no motion viewing conditions. Note that we asked them to give their overall impression of the different paths regardless of interactivity or motion cueing. We also asked participants to rate the magnitude by which one condition is stronger than the other. With the data at hand, curvilinear paths were overall perceived to be 67% stronger over straight paths for those who experienced curved paths as more

intense. For those who found that straight paths resulted in a stronger sensation of vection, straight paths were on average 73% more intense compared to curved paths.

3.2.5. Discussion

Increasing turn velocity can enhance optic flow-induced vection. During experiment 2, increasing turn velocity increased **vection intensity** ratings by about 34% going from straight paths to narrow turns (24°/s), after participants familiarized themselves to the setup and tasks during experiment 1. Vection intensity was greater for higher turn velocities for almost all conditions in both experiments except when participants used the chair to control their locomotion in experiment 1 and when they used the joystick to control their locomotion in experiment 2. This overall benefit of increasing turn velocity was corroborated by participant responses during the post experimental interview, where almost 90% of participants rated stronger vection for curvilinear trajectories over straight path conditions.

A possible explanation for lower vection intensity ratings during active locomotion conditions may be that controlling locomotion could have distracted participants from paying attention to their vection experience and/or the visual motion stimulus partly because active locomotion in general may require additional attention and familiarization and partially because participants experienced some difficulty and discomfort when using the chair to actively locomote (see discussion in subsection 3.5 for more detail). Their altered attention and possibly also viewing/fixation behavior may thus have impacted the perception of the motion stimulus and consequently their experience of vection. Possibly the increase of turn velocity and associated beneficial effects could have been countered by increasing difficulty executing the locomotion task for higher turn velocities. The resulting, systematic cancellation could have overall reduced facilitation of vection for higher turn velocities, particularly for experiment 1 where participants were still unfamiliar with the procedure.

Vection intensity overall appeared to have increased in experiment 2 over experiment 1. The reason for this effect may lie in the familiarization with the procedure, particularly locomotion control so that participants may have paid more attention to the visual stimulus motion and their vection experience.

Vection latency was generally lower for narrower turns, particularly when the increase in turn velocity was greater, such as 8°/s vs. 24°/s or 0°/s vs. 24°/s. Interestingly, the overall benefit of turn velocity on vection latency was not as pronounced in experiment 1 as it was in experiment 2 despite the fact that stimulus conditions we tested in experiment 1 were identical to those repeated in experiment 2 with the exception of more repetitions and the addition of the straight path condition. Overall, vection latency was reduced by about 20% when going from straight paths to narrow turns (24°/s) after participants were familiar with the routine during experiment 2.

A possible explanation for this effect may again be familiarization of participants with the overall procedure and locomotion control in particular. We think that especially the vection latency metric was subject to training effects. Participants who were new to the procedure and distracted by controlling locomotion could have unsystematically introduced a delay in reporting vection latency and thus, introduced sufficient noise into our data so that a an effect of higher turn velocity was statistically significant for experiment 2 (after sufficient familiarization), but not so for experiment 1.

Although V**ection occurrence** was least consistently affected by turn velocity compared to vection latency and vection intensity in particular, we found that overall, vection was more likely to occur for greater turn velocities. The likelihood of vection increased by about 9% going from a straight path to narrow turns (24°/s) after familiarization with the system (experiment 2); however, more data is necessary to make a strong statement.

Similar to vection intensity and vection latency, vection occurrence also seemed to be affected by familiarization of participants with the setup. In experiment 1, participants were less likely to experience vection under certain conditions when actively controlling their locomotion compared to passive conditions, but this effect disappeared in experiment 2 after they gained more experience with the procedure.

In the context of our hypothesis (see subsection 1.3.1), we asked whether increasing turn angles and thus narrower turns are overall beneficial to visually induced vection when dynamic perspective renderings and binocular motion information from an optic flow field are available. We found evidence, that the structure of the visual

information such as pattern frequency as a function of velocity was a predominant factor that impacted vection. While presentation method such as 3D projection may relatively affect vection, we confirmed that angular velocity is a salient vection-inducing factor as evidenced by the vection literature (Allison et al., 1999; Riecke, Schulte-Pelkum, Avraamides, et al., 2006; Riecke, 2006; Trutoiu et al., 2009). Thus, increasingly narrow turns are possibly more potent in inducing vection compared to wider turns and straight paths (zero turn velocity) in particular. It seems that motion simulations can easily be enhanced at minimal effort by predominantly applying curvilinear trajectories and particularly narrow turns to the simulation scenario.

3.3. Motion cueing

In the context of our hypothesis (see 1.3.2), we were interested if small, physical motion cues can enhance visually induced vection. Not much has been researched in this direction, but there is evidence that minimal motion cues of a couple of centimeters may enhance vection and particularly reduce vection latency (Riecke, 2006; Schulte-Pelkum, 2007 [experiment 5]; Wong & Frost, 1981). Particularly Riecke (2006) found a benefit of using simple, off-the-shelf hardware that he turned into an embodied locomotion and motion cueing interface. In the same spirit, we aimed to use an affordable off-the shelf locomotion interface in form of a gaming chair that afforded motion cueing to see if it as well facilitated vection. In Riecke's study, however, motion cueing was not explicitly disambiguated as a factor of his experimental design and our goal here was thus to explicitly look at conditions of motion cueing using the same device for all conditions. Our findings of the factor motion cueing and its effect on vection are summarized in the following subsections.

3.3.1. Main effects of motion cueing on vection during experiment 1 and experiment 2

The purpose of this subsection is to show the effect of motion cueing on the three vection metrics vection intensity, latency and occurrence. We first explored the relative contribution (main effects) of motion cueing averaged over turn velocity and interactivity and then investigated how effects of motion cueing may have interacted with other

factors of this study, particularly interactivity. In subsection 3.3.2, we thus disambiguated interactivity from motion cueing to isolate vestibular/somatosensory contributions of physical motion cueing to vection. We then corroborated our quantitative findings with post-experiment interview data.

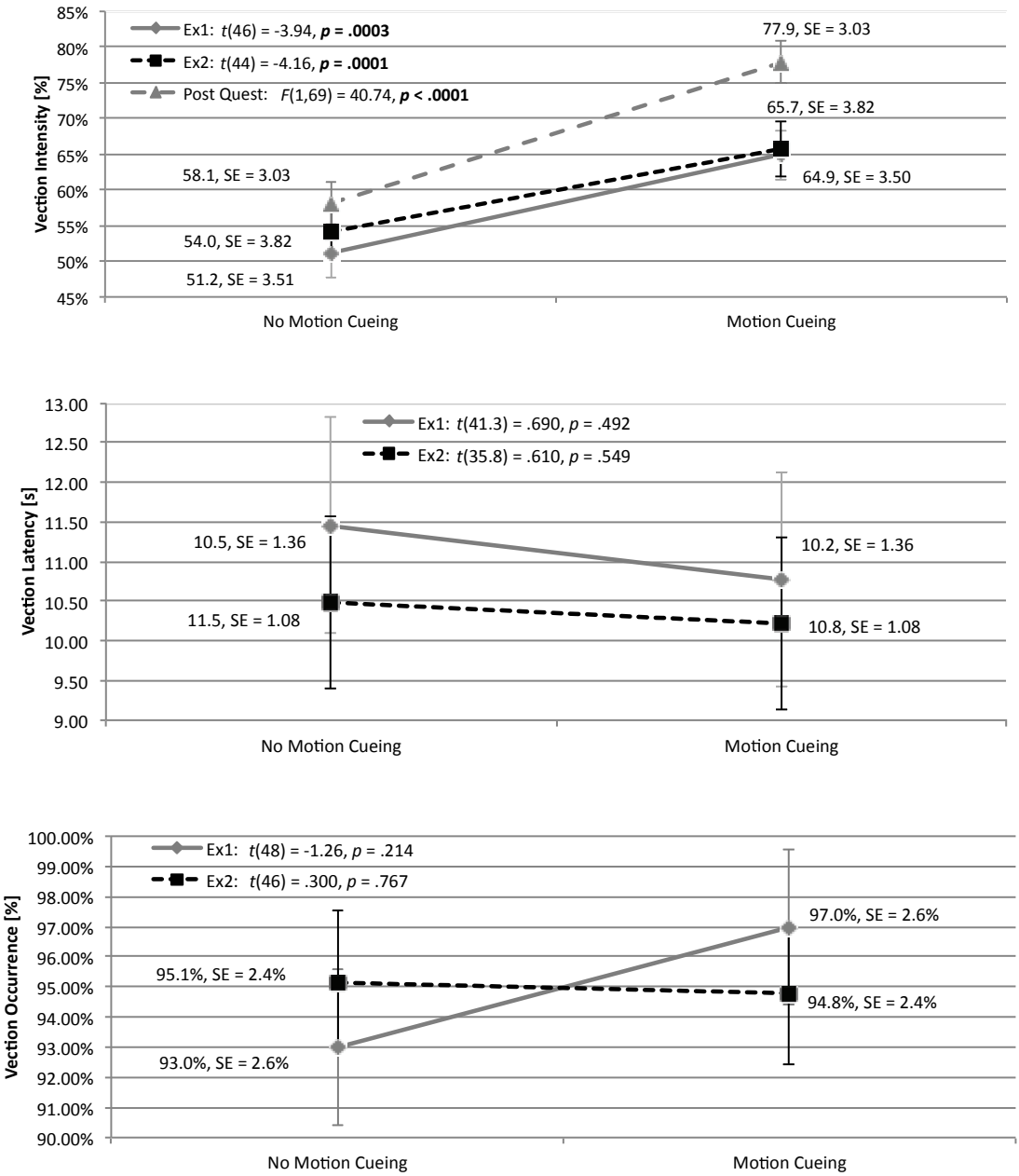

Figure 3-4: Data from both experiments in three plots, one for each vection metric. Data labels contain least squares means and standard errors (SE). Legend contains difference statistics. Whiskers represent the standard error. p-values typeset in bold highlight significant differences.

Figure 3-4 above depicts the main effects of turn velocity on our three vection metrics in a side-by-side comparison of both experiments. Overall, the trend lines indicate a positive effect of motion cueing on vection for all vection metrics in both

experiments. The beneficial effect of motion cueing on **vection intensity** and **latency** seemed more pronounced for experiment 2 over experiment 1, possibly due to familiarization mentioned in subsection 3.2.5. Interestingly, participants were equally likely to experience vection (**vection occurrence** measure) in no motion and motion cueing conditions in experiment 2 despite the familiarization they experienced up until that point (Figure 3-4, bottom plot). Surprisingly, participants seemed more likely to perceive vection during conditions of motion cueing compared to no motion cueing in experiment 1, although this trend did not reach significance, and more participants are necessary to make any clear statements. In fact, only vection intensity was significantly affected by motion cueing (experiment 1: $F(1,46) = 15.53$, $p = .0003$, experiment 2: $F(1,44) = 17.31$, $p = .0001$) whereas vection latency (experiment 1: $F(1,41.3) = .480$, $p = .492$, experiment 2: $F(1,35.8) = .370$, $p = .549$) and occurrence were not (experiment 1: $F(1,48) = 1.59$, $p = .214$, experiment 2: $F(1,46) = .090$, $p = .769$).

3.3.2. Passive no motion vs. motion cueing

In the previous subsection, we looked at the overall effect of motion cueing on vection. That is, we averaged responses over the other independent variables interactivity and turn velocity. As comparing the two active conditions can be problematic due to the difference in interfaces, we only compared the two passive motion conditions in the following subsection. This should remove potential confounds of interface usability and thus more directly assess potential impacts of motion cueing. Figure 3-5 shows indeed significant vection-facilitating effects of motion cueing in the passive conditions as hypothesized in 1.3.2. Note: In the context of motion cueing, vection latency and occurrence were not significantly affected and thus excluded from the comparison below.

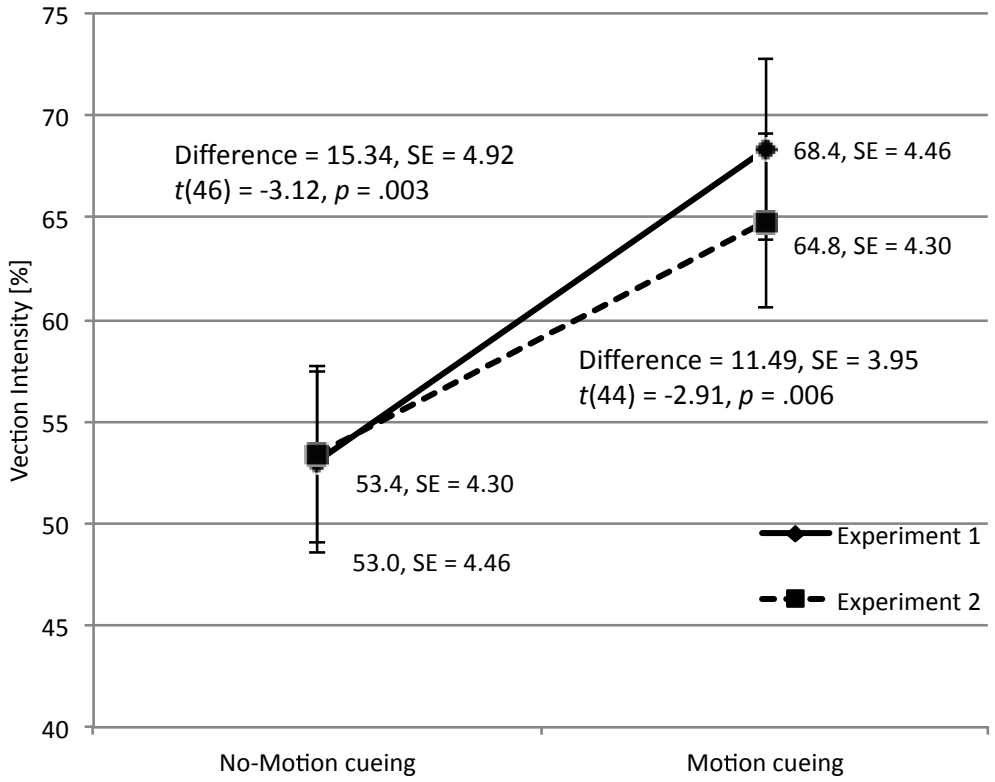

Figure 3-5: Vection intensity as a function of no motion vs. motion cueing during passive locomotion. Whiskers depict the standard error (SE). Trend lines are annotated with difference statistics.

Figure 3-5 revealed, as to be expected, that the overall trend remained the same. Least square means differences were slightly greater over those depicted in Figure 3-4 (top). Again, there is strong evidence that motion cueing indeed increased vection intensity ratings if we control for differences of interface.

We found, that the overall perceived magnitude of vection was higher when physically moving, but vection latency and occurrence were not significantly affected. We conducted a post experiment interview and found possible explanations for this effect. The relevant interview data is summarized and explained in the following subsection.

3.3.3. Post experiment interview data

In an interview after the experiment, we asked participants to rate the overall intensity of their vection experience for conditions of physical stationarity versus motion cueing on a scale between 0% (implied no vection) and a 100% (most intense sensation of vection according to baseline). The response data are plotted in Figure 3-4 (top) under the label “Post Quest”, which stands for post-experiment questionnaire. Participants quite accurately remembered their vection experience and, as the plot depicts, responded according to their average trial-by-trial estimates. In line with our quantitative findings, the interview data showed that motion cueing significantly increased vection intensity compared to conditions of physical stationarity.

After they reported overall vection intensity estimates, we asked them how they felt about the physical motion cues we used in the study and encouraged them to describe any benefits and downsides of the motion paradigm that came to mind:

“What did you think of the physical motion used in the study (controlling the chair/being pushed)? What was the best/worst about it?”

P1: Worst: turning because you lose track. Best: increase/decrease speed more intuitively. Gave a more real sensation of motion when watching or using the joystick.

P2: Worst: it could be distracting. Best: motivates the sensation of motion

P3: Worst: hard to fine tune because it’s sensitive. Best: more involved in the environment and you feel like you're there.

P4: Worst: when I move myself I felt more nauseous, less natural. Best: being pushed is more natural.

P5: More motion sickness when being pushed and watching it passively.

P6: Worst: woodwork dug into my hands when holding the chair for sharp turns. Best: more sense that you are in the world.

P7: Worst: start of motion is jerky and it's nauseating, hitting the box feels like you're actually hitting something. Best: feels sort of real, sense of getting car sick.

P8: Worst: can't think of any. Best: you feel more into it and engaged.

P9: Worst: pushing was almost like watching, motion was not really a benefit. Motions made me dizzy. Best: none.

P10: Worst: slow start, brings on the most intense motion sensation. (Participant did not enjoy the motion sensation.) Best: the s-curve (training phase) is the most enjoyable.

P11: Worst: none. Best: it lets you feel like you are moving (more realistic).

P12: Worst: you may get motion sick, particularly when you're getting pushed. Best: it does get you in a little bit more and it would prevent you from being still, this way it engages your whole body and keeps you awake longer.

P13: Worst: if it's going too fast you may get dizzy, but did not happen to me though. I just got a little disoriented. Best: you felt more in that world and be part of it.

P14: Worst: hard to control. Best: more sense of physical moving.

P15: Worst: easy to overcompensate (too far left/right, etc. It needs some tweaking). Best: more interactive when using your body.

P16: Worst: hard to control motion. Best: felt like moving more.

P17: Worst: motion sickness. Best: being pushed because it's a surprise and unexpected and it gives you more reality.

P18: Worst: when using the chair I used more my hands than my body, also the setup did not fit my height. Best: better to be pushed.

P19: Worst: I had to go back often because hard to control. Best: felt like pulling a car.

P20: Worst: dizziness. Best: feel like I was actually moving more.

P21: Worst: getting used to. Best: moving with the cube was more interactive.

P22: Worst: not having control. Best: more exhilarating/exciting.

P23: Worst: felt a bit off, did not map well. Best: feels better.

P24: (No answer recorded, subject had to leave.)

From the responses at hand, we attempted to visualize patterns in order to identify what benefits or problems were commonly associated with our motion cueing approach. After the interview, we identified categories of repeated mentionings in the responses, counted the frequency of responses for each category, summarized categories and associated frequencies in a table (see Table 3-3). Based on the table, we

vizualized the information in a radar chart (see Figure 3-6). Note that individual participant responses may have contributed counts to more than one category.

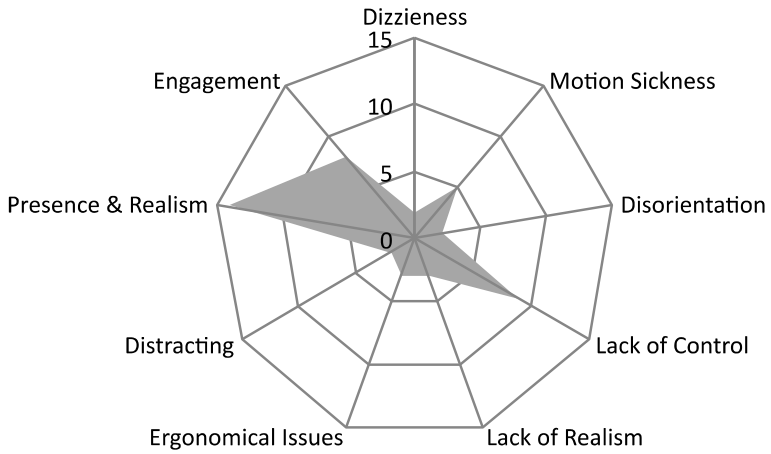

Figure 3-6: Visualization of commonly reported benefits and issues associated with the Gyroxus motion paradigm. The shaded area represents the response spectrum across categories. Count represents number of responses from the 24 participants tested.

Categories	Count
Dizzieness	2
Motion Sickness	5
Disorientation	2
Lack of Control	9
Lack of Realism	3
Ergonomical Issues	3
Distracting	2
Presence & Realism	14
Engagement	8

Table 3-3: Nine identified categories and associated response frequencies.

Participants' verbal responses about our motion cueing paradigm helped to interpret our quantitative findings summarized in Figure 3-4 as well as Figure 3-5. The chart in Figure 3-6 shows that motion cueing seemed highly beneficial for a sense of presence and realism and it may have facilitated engagement. On the downside, the motion paradigm was associated with motion sickness and oher sources of discomfort as a result of ergonimical issues, such as lack of adjustability to various body sizes. These findings may explain why participants could have been distracted and thus failed to pay proper attention to the motion stimulus, their vection experience or accurately report vection onset.

3.3.4. Discussion

Overall, motion cueing seemed to have enhanced optic flow based vection, although these trends reached significance only for vection intensity. Overall, vection intensity increased by 22% for the motion cueing over the no motion cueing condition in experiment 2, once participants were familiar with the setup and procedure. We think that vection latency and occurrence remained largely unaffected because the relative contributions of the motion paradigm were either too small and/or vection latency may have been an unreliable measure considering the occurrences of motion sickness, ergonomy and other issues that are elaborated in more detail in subsection 3.5. Despite the shortcomings of our motion paradigm implementation, participants subjectively felt more part of the virtual world and it becomes apparent that the chair may have enhanced the overall user experience particularly when precise control of locomotion is not necessary. Thus, our hypothesis (see subsection 1.3.2) was only partially confirmed and we have to conlcude, that the minimal motion cueing approach in our study was not as successful as anticipated, particularly when weighing discomfort and motion sickness associated with the Gyroxus implementation against the increase of vection intensity only. Further research is needed to disentangle motion ceuing and problems associated with one specific implementation by investigating additional motion paradigms.

3.4. Interactivity

As mentioned in 1.3.3, the lack of direct comparisons between conditions of vection in which participants passively experience locomotion or during which they actively control their locomotion through a simulated environment make it problematic to draw conclusions about the effect of interactivity on vection because methods and visual stimuli differ quite considerable between studies. In the light of recent technological advancements that made interactive VR and gaming applications commercially available and widely accepted, we asked the question if interactivity does somehow affect vection. Based on related literature, it seemed that interactivity could possibly enhance vection either through additional non-visual motion cues (Crowell et al., 1998; Mittelstaedt & Mittelstaedt, 2001; Wexler et al., 2001) and/or mitigation of adverse side effects associated with vection such as motion sickness (Rolnick & Lubow, 1991). To confirm if possible, non-visual motion cues enhance vection, we directly compared conditions of passive and active locomotion control. If actively controlling locomotion does enhance vection, then this aspect should be applied to motion simulations whenever it suits the simulation scenario. The following subsections summarize the effects of the factor interactivity on vection in the context of our study.

3.4.1. Effects of interactivity on vection during experiment 1 (training) and experiment 2 (main study)

In the current subsection, we compared conditions of interactivity and their effect on vection intensity, latency and occurrence. First, we summarized main effects of interactivity averaged over turn angle and motion cueing. For experiment 1, we also detected an interaction effect between interactivity and turn velocity, which is mentioned in this summary as well. We then disambiguated interface (joystick or chair) and closely looked at how the interface and consequently motion cueing affected relevant vection metrics in the context of interactivity. We then summarized our findings from a post experiment interview to corroborate our quantitative data.

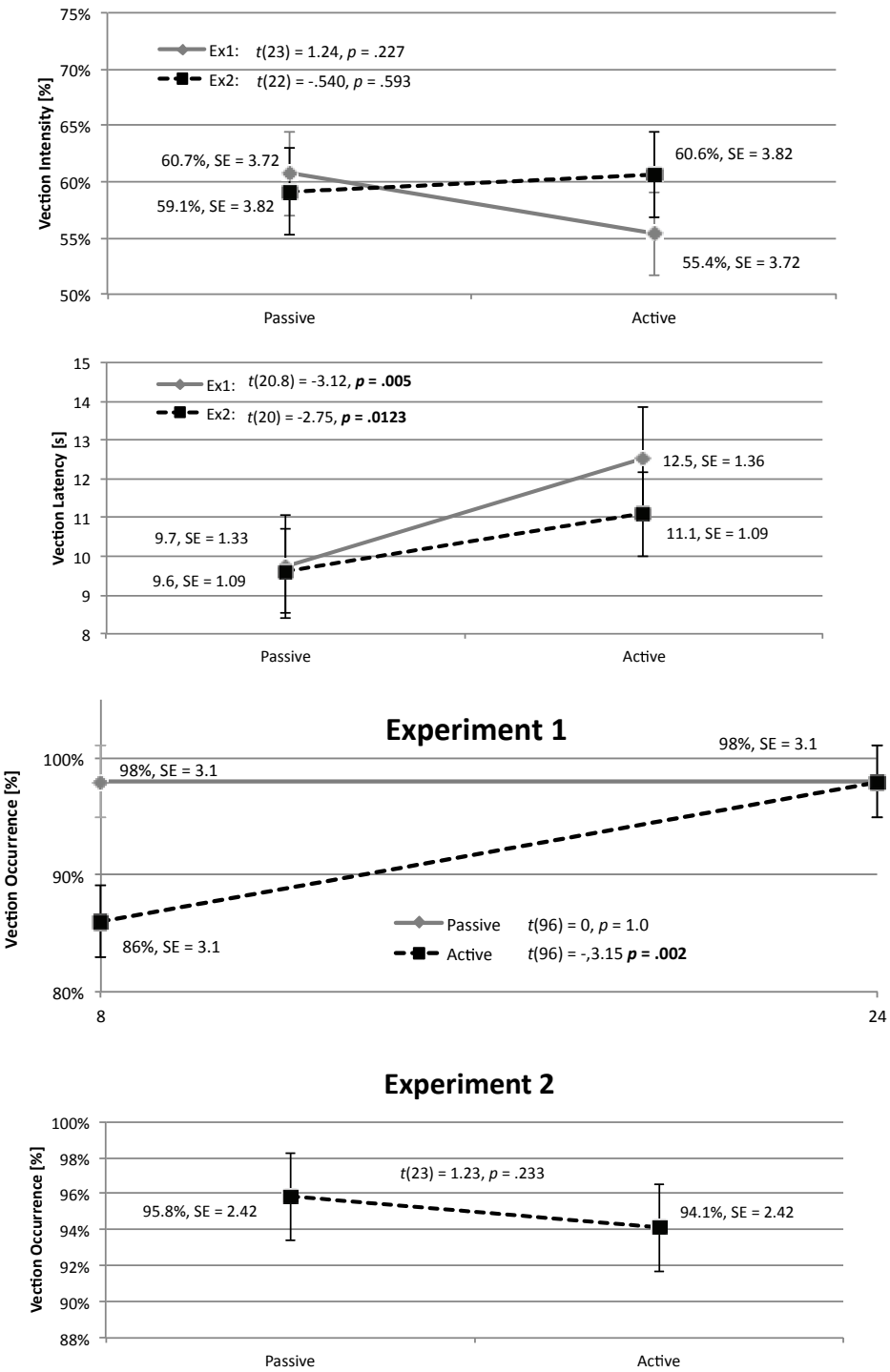

Figure 3-7: Plots of vection data for both experiments. The latter two plots show vection occurrence data for experiment 1 and 2 in separate plots due to an interaction effect between interactivity and turn velocity in experiment 1. Significant differences are typeset in bold. Whiskers represent the standard error (SE).

Main effects of interactivity on the three vection metrics are summarized in Figure 3-7. **Vection intensity** seemed to slightly decrease in experiment 1 when participants actively controlled their locomotion compared to conditions in which they passively experienced a pre-recorded motion stimulus. In experiment 2, participants rated vection to be more intense during actively controlling their locomotion compared to conditions of passive locomotion. Vection intensity, however, was not significantly affected by interactivity in experiment 1 ($F(1,23) = 1.54$, $p = .228$) as well as in experiment 2 ($F(1,22) = .290$, $p = .594$).

Interestingly, **vection latency** was overall significantly higher for conditions where participants controlled their own locomotion compared to conditions where they passively watched the motion stimulus in both, experiment 1 ($F(1,20.8) = 9.74$, $p = .005$) and experiment 2 ($F(1,20) = 7.58$, $p = .012$), although this effect was less pronounced in experiment 2.

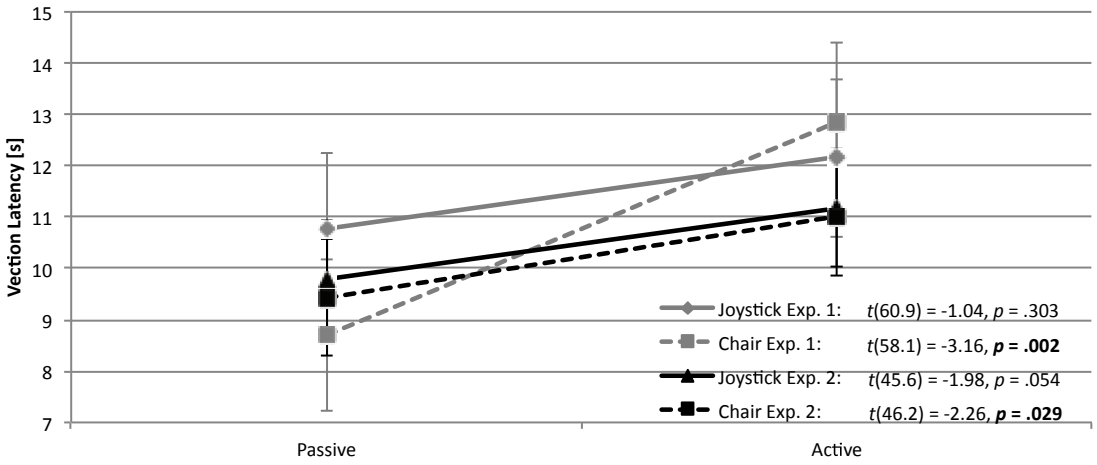

Figure 3-8: Vection latency responses as a function of interactivity for both experiments with disambiguation of interface device. Legend lists difference statistics. Statistically significant differences are typeset in bold. Whiskers represent the standard error (SE).

To investigate how joystick versus chair control might have differentially affected our results, we plotted vection latency data separately for those devices in Figure 3-8 and performed post-hoc t-test depicted in the plot legend. Participants took marginally

longer to experience vection using the joystick (about 1 second) whereas they took significantly longer when using the chair to actively control their locomotion (about 4 seconds). This overall effect remained in experiment 2, but the difference between joystick and chair was significantly reduced (see Figure 3-8).

The **vection occurrence** data plotted in Figure 3-7 (last two plots) and the F-test summary (see Table 3-1) indicate that there was an interaction effect between interactivity and turn velocity in experiment 1 ($F(1,96) = 4.97$, $p = .028$). That is, vection occurrence was less likely, when participants actively controlled their locomotion in conditions of small turns (8°/s) compared to large turns (24°/s). This interaction effect between interactivity and turn velocity disappeared in experiment 2, where interactivity did not seem to have decreased the likelihood of vection occurrence ($F(2,184) = .800$, $p = .450$); see Table 3-2.

3.4.2. Active vs. passive (no motion cueing)

In this subsection, we directly compared interactivity and excluded motion cueing as a possible confound and to investigate interactivity based on the joystick paradigm only. We thus compared responses from stationary participants that were just watching the scene to responses of stationary participants who were using a joystick. Based on the main effects summary, vection latency was the only vection metric that was significantly affected by interactivity. We thus focused our comparisons on vection latency only.

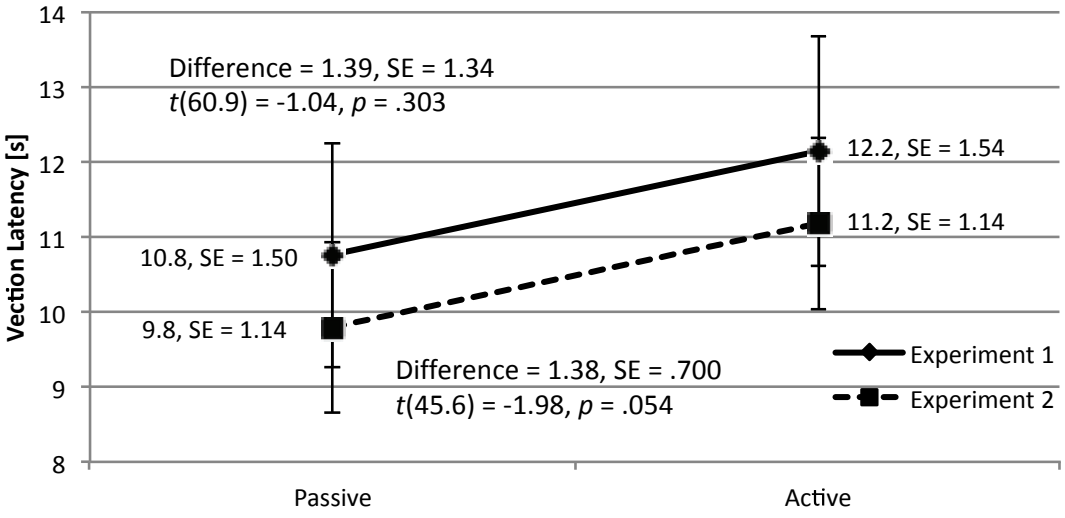

Figure 3-9: Vection latency as a function of passive vs. active (joystick) locomotion control in conditions of no motion cueing. Whiskers represent the standard error (SE).

Figure 3-9 shows a non-significant trend towards increased vection onset latency for the active joystick condition compared to passive passively viewing the simulation without any motion cueing. Note that participants overall perceived vection earlier in experiment 2.

3.4.3. Active vs. passive (motion cueing)

This subsection compares interactivity in moving participants to investigate interactivity based on the chair paradigm only. That is, conditions of participants being passively pushed in the chair compared to conditions where participants actively moved themselves in the chair to control their locomotion through VR. Figure 3-10 shows that moving participants took significantly longer to experience vection in the active versus passive condition. Interestingly, this effect was less pronounced in experiment 2, potentially due to training effects.

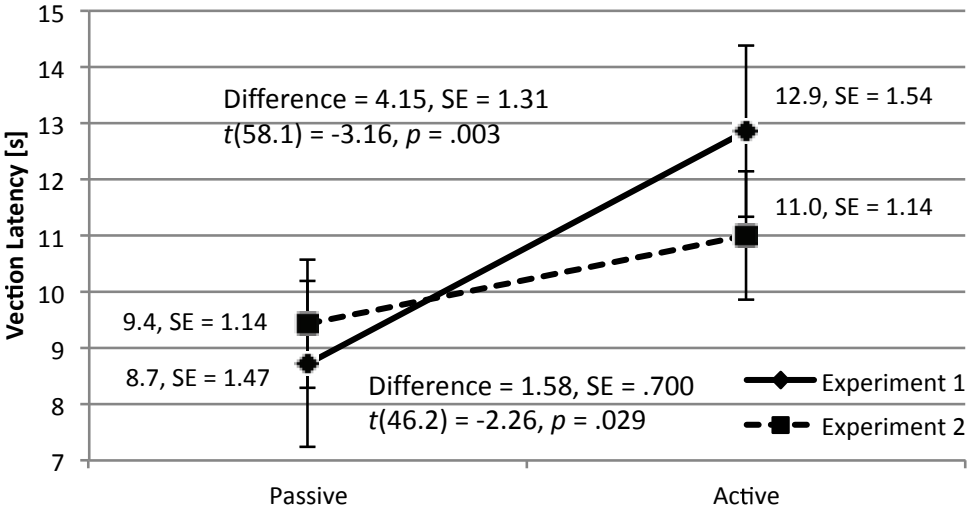

Figure 3-10: Vection latency as a function of passive vs. active (chair) locomotion control in conditions of motion cueing. Whiskers represent the standard error (SE).

3.4.4. Post experiment interview data

In the post-experimental interview, we asked participants to rate the overall intensity of their vection experience when passively and actively locomoting through the virtual world and for conditions of physical stationarity versus motion cueing. The corresponding data are plotted in Figure 3-11.

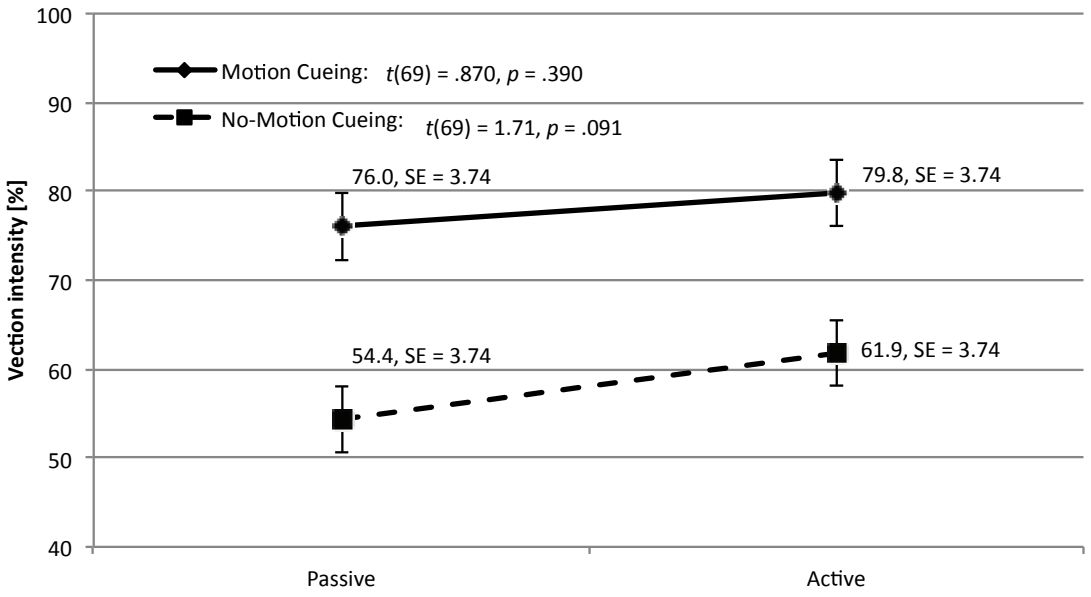

Figure 3-11: Post-experiment interview data. Vection intensity plotted as a function of active versus passive conditions for both, motion and no motion cueing conditions. Legend contains the difference statistics. Whiskers represent the standard error (SE).

As evident in Figure 3-11, participants overall felt that vection intensity was slightly higher for active than passive conditions regardless of whether they experienced physical motion cues or not. However, this effect was not statistically significant for neither condition of no-motion cueing ($t(69) = 1.71$, $p = .091$) nor motion cueing ($t(69) = .870$, $p = .390$).

3.4.5. Discussion

Overall, the effect of interactivity on our three vection metrics seemed to be affected by a possible training effect or familiarization that occurred during experiment 1 and thus affected vection metrics in experiment 2. Participants seemed to overall report higher vection intensity ratings, lower vection latency and more likelihood of vection occurrences for experiment 2 compared to experiment 1, although only effects of interactivity on vection latency reached statistical significance in both experiments.

Vection intensity was not significantly affected by interactivity for both experiments across. Based on the post-experiment interview data, interactivity only

marginally improved vection intensity, a mere 6% difference. However, there was a noticeable trend towards higher vection intensity for experiment 2 in conditions of active locomotion vs. passive locomotion. This effect contrasted the opposite trend in experiment 1, where vection intensity ratings decreased for active locomotion. It seemed that this effect of active locomotion on vection intensity was mitigated over time, possibly due to familiarization of participants to the virtual reality setup and the chair control in particular, see subsection 3.5.

Interactivity significantly increased **vection latency** for active conditions. Participants took almost exactly as long to experience vection when passively locomoting through the virtual environment in experiment 1 compared to experiment 2, but they took significantly longer in both experiments when they actively controlled locomotion. In experiment 1, participants took on average 3 seconds longer to perceive vection compared to the passive condition. Interestingly, this delay was cut in half during experiment 2 where participants took on average 1.5 seconds longer to perceive vection for active locomotion. Overall, it took participants 16% longer to experience vection when they actively controlled locomotion compared when they passively experienced locomotion.

Below, we discuss several possible explanations as to why 1) vection latency was greater for active vs. passive locomotion conditions and 2) vection latency was overall shorter during experiment 2 vs. experiment 1.

In regards to the first point, we suspect that participants took longer during active locomotion control to perceive and/or rate vection because the locomotion task involved some cognitive resources, focus and attention that may have altered their viewing and fixation patterns and consequently their vection experience. Additionally, this preoccupation may have introduced an unsystematic delay in reporting vection onset so that the responses for this metric may be biased. Aside from the locomotion task, some participants mentioned during the experiment that active self-motion was troublesome and made them sick (possibly due to radical changes in navigation/overcompensation) which may have exacerbated their distraction from the task thus resulting in inaccurate reports of vection onset.

In regards to the second point, the decrease of overall vection latency for active locomotion conditions in experiment 2 might be explained by training and familiarization that occurred during experiment 1 so that participants were less distracted and more at ease with the procedure which in turn allowed them to pay attention to the motion stimulus, the navigation task and the reporting of vection. Additionally, the introduction of the straight path trajectory could have reduced vection latency responses. Participants may have had less difficulty in controlling their locomotion when travelling on a straight path and thus were less distracted or preoccupied. In turn this may have resulted in conditions where participants actively controlled their locomotion, but their vection experience and/or vection reporting behavior remained largely unaltered.

We think that the previously mentioned factors may have also affected the **vection occurrence** metric, particularly in regards to a possible training effect that seemed to have occurred during experiment 1.

The interaction effect between interactivity and turn velocity we detected in experiment 1 disappeared in experiment 2; possibly a result of practice and less noisy data. The interaction effect occurred in the active conditions only and affected the 8°/s, but not the 24°/s level of turn velocity. In other words, while responses for passive locomotion did not change over turn velocity, responses for active locomotion changed in that vection occurrence was significantly lower for the 8°/s than the 24°/s level. At the 24°/s level, the likelihood of vection between passive and active was identical.

It is not fully clear to us as to why we observed this effect, particularly since it is conceivable that wider turns (8°/s) should generally be easier to navigate than narrow turns (24°/s). Thus, participants should have encountered less difficulty and distractions during conditions of wide turns compared to conditions of narrow turns. At this point we assume that a higher number of observations are necessary to make any clear statements.

In the context of our hypothesis (see 1.3.3), interactivity did not predominantly enhance vection. On one hand, actively controlling locomotion may result in a more intense sense of self-motion and may be more engaging. On the other hand, active locomotion seems to come at the cost of longer vection latencies (see possible causes

mentioned in 3.5) and, in case of using the chair, potential signs of motion sickness. While additional training and improvements to the locomotion control paradigm may mitigate this problem, further research is necessary to confirm and extend these findings.

3.5. Joystick vs. Gyroxus gaming chair

Riecke (2006) showed that participants reported vection earlier and with a greater magnitude when they used a customized wheelchair compared to traditional button-press or joystick control paradigms when actively locomoting through a projected 3D world. In light of these findings, we were interested if consumers or designers of vection-based motion simulators may forgo the customization process and just use an off-the-shelf gaming chair that allows locomotion control and motion cueing similar to the wheelchair that Riecke used in this study. Our hypothesis stated in subsection 1.3.4 was that if gaming chairs (much like the wheelchair) are a good alternative to traditional joysticks, then participants should have a comparable level of control over their locomotion in VR and prefer the more embodied chair over the joystick. The summary below addresses this question.

In the following section, we directly compared the two input devices participants used in our experiments to control their locomotion through the virtual world. The first subsection briefly looks into how interface affected the two most significant vection metrics: vection intensity and vection latency. The second subsection summarizes reports and data from our post-experiment interview to shed additional light on how participants felt about using these two interfaces.

3.5.1. *Effects of interface on vection*

Figure 3-12 below summarizes our active control vection intensity data collected during both experiments. Participants generally experienced a significantly stronger sense of vection when using the chair compared to using the joystick, regardless of condition. This trend is in line with the summary of post-experiment data depicted in Figure 3-11 in subsection 3.4.4.

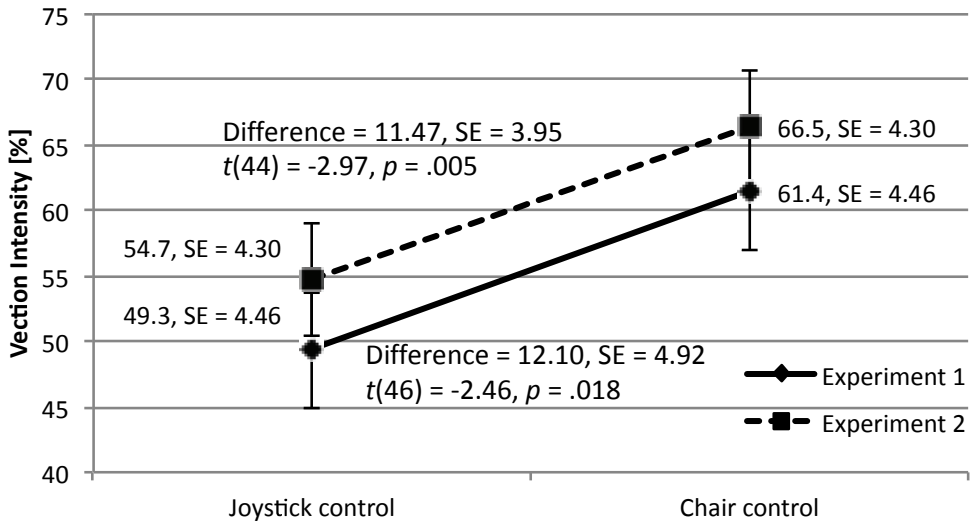

Figure 3-12: Vection intensity as a function of joystick control (active, no motion cueing) and chair control (active, motion cueing). Whiskers represent the standard error (SE).

Aside from stronger vection experiences, vection latency was reduced when the chair was used to provide physical motion cues to the passive participant; see Figure 3-8 in subsection 3.4.1. Overall, the chair seems suitable to enhance the overall vection experience when it is used for passive locomotion or for active locomotion in absence of specific navigation requirements as discussed in more detail in subsection 3.3.3.

3.5.2. Post-experiment interview: precision and intuitiveness

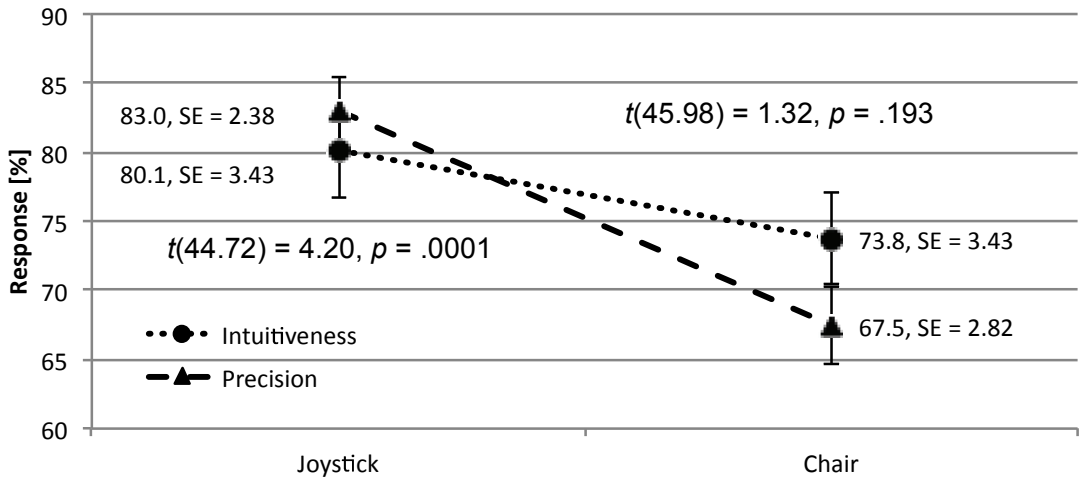

Figure 3-13: Intuitiveness and precision as a function of interface: Which interface was more useful to control locomotion? Whiskers represent the standard error (SE).

During the post-experiment interview, we asked participants how intuitive it was to control the chair and joystick and how well they were able to navigate with either device. For both questions, they responded on a scale between 0 and 100 (0 = not at all, 100 = very intuitive/precise). As shown in Figure 3-13, participants rated joystick-control to be more precise over the chair as a velocity control paradigm in VR.

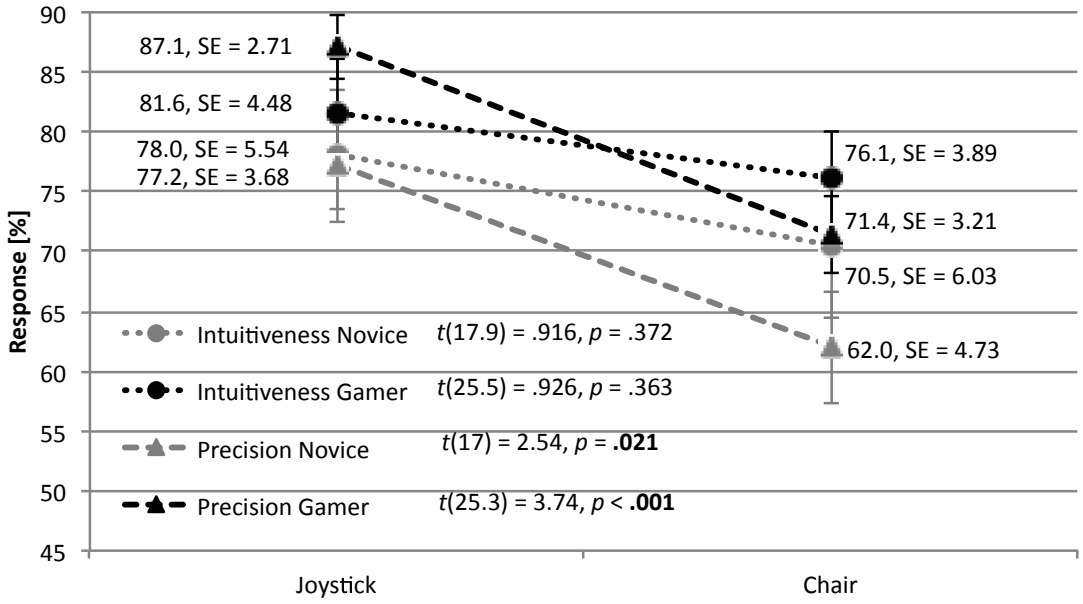

Figure 3-14: Responses of novices versus gamers on intuitiveness and precision for the joystick and Gyroxus gaming chair. Whiskers represent the standard error (SE).

We additionally asked participants if they frequently play computer games and defined participants as gamers if they played 3D computer games for more than an hour a day. Figure 3-14 depicts intuitiveness and precision as function of interface for novices and gamers. While the trend remained in favor of the joystick, gamers overall experienced the gaming chair to be more intuitive and precise compared to novices who may have struggled more when using the chair.

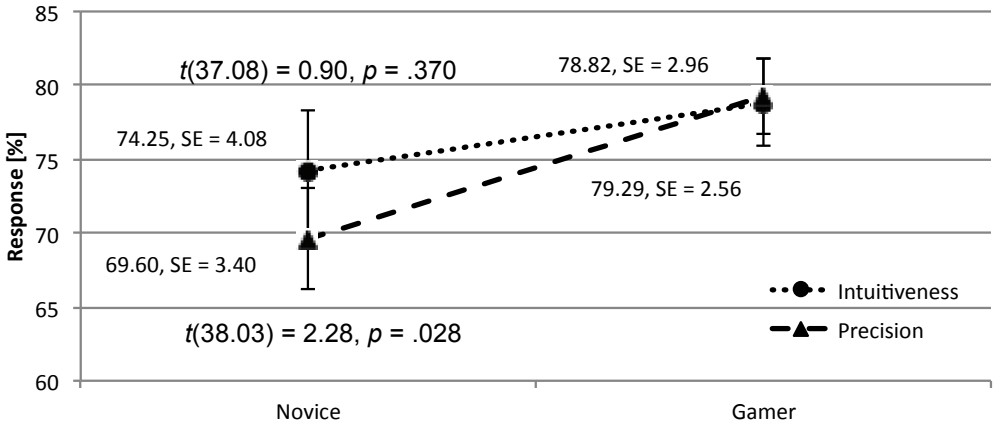

Figure 3-15: Intuitiveness and precision as a function of gaming experience. Whiskers represent the standard error (SE).

As depicted in Figure 3-15, overall, prior gaming experience affected perceived usability for the precision, but not the intuitiveness measure. Gamers perceived input devices about 10% more precise than novices.

To corroborate the intuitiveness and precision data outlined above, we directly asked participants about which interface they preferred and why:

"Overall, would you prefer to use the chair or joystick for navigating in virtual worlds?"

P1: Joystick because there's more control. Chair would often go back/forward in the beginning or I pass the cube.

P2: Joystick, it is more intuitive and I use similar things for painting.

P3: Joystick because I can control it better.

P4: Joystick because I can control it better.

P5: Depends on the task, joystick is better for delicate tasks, chair is more engaging and better for controlling the speed (better than the joystick in this case).

P6: Chair, it's more fun.

P7: Joystick, because it's easier, better control.

P8: Chair definitely.

P9: Joystick, it's easier to control.

P10: Joystick.

P11: Joystick, easier and you most likely make a big mistake on the chair

P12: Chair would be a lot more fun.

P13: Joystick in the beginning, because it's easier to hold something than to use your whole body. But after you get used to it I'd prefer the chair.

P14: I prefer the chair but I'm not good at it.

P15: Joystick, because it's easier to control.

P16: Joystick.

P17: Joystick.

P18: Joystick.

P19: Joystick, because I felt more comfortable with it because everything was in my hand.

P20: Joystick is easier, but the chair is more fun.

P21: Chair, because it's more fun when you move with it.

P22: Chair for fun, joystick for control.

P23: Chair.

P24: Chair, because it's more fun and you're more into it. If I want to master the game I'd use the joystick.

We found, that over two thirds of participants preferred the joystick because they felt a greater sense of control and confidence to accomplish the mission goal (tightly follow the green cube). The remaining third preferred the chair for navigating in virtual worlds. It became evident, that participants would have enjoyed using the chair if there was no tightly controlled navigation target. Our particularly strict navigation guidelines forced them to precisely control the chair which apparently was not the strength of the device. As a result, some participants were somewhat frustrated particularly during the training sessions in experiment 1.

3.5.3. Discussion

Overall, participants chose the chair for fun and exhilaration and would prefer it after some more practice and experience with it. Generally, the joystick was perceived to

be easier to use compared to the chair, which was corroborated through the post-experimental questionnaire data on usability in the beginning of this section.

However, gamers apparently found the chair more intuitive to use and more precise in accomplishing the task compared to novices. Possibly, gamers may have had prior experience with a similar, gaming interface device and/or they were less distracted with certain aspects of the simulation that were more familiar to them, but not to the novice. This novelty factor may have distracted novices more from the (navigation) task compared to gamers and consequently, novices may have had less cognitive resources available to focus on the navigation task, focus on the motion stimulus or their vection experience and properly report vection. Further investigations of effects of gamers vs. novices on vection are necessary for a prudent selection of participants and the proper inclusion of prior gaming experience into the experiment design model.

When looking at the post experiment interview data (see subsection 3.5.2), it became evident that the use of the chair was somewhat less intuitive compared to the joystick. Answers to the question “What did you think of the physical motion used in the study (chair/pushing)?” often referred to the chair as being difficult to control (see Figure 3-6 in 3.3.3). Participants mentioned oversensitivity of the device, “jerky” motions, poor mapping between body and camera motion, as well as difficulty to finely adjust motions using the body for persons that are heavy or tall. Those participants relied more heavily on actuation of chair-motion by hand using the mounting plate of the joystick, which turned out to be somewhat painful in at least one participant as the wooden corners of the plate dug into his hands.

Half of the participants who preferred the chair were gamers and the other half novices so that chair preference was not necessarily dependent on prior gaming experience. As expected, participants with prior gaming experience seemed to be more confident in controlling their locomotion within the virtual reality system based on the precision and intuitiveness ratings (see Figure 3-13 and Figure 3-15) although only precision ratings were significantly affected by both, device and level of experience.

In the context of our hypothesis, the Gyroxus gaming chair was not as easy and intuitive to use, contrary to manufacturer claims. Its benefits of embodied motion control

were offset by the lack of perceived control and the rather clumsy implementation of the motion paradigm. However, the chair overall enhanced vection when used to provide passive motion cues, which was not the intention of the manufacturer. As the evidence stands, at least the Gyroxus gaming chair will not replace traditional interfaces such as joysticks anytime soon. This does not mean, however, that gaming chairs or other interfaces will not. The wheelchair used by Riecke (2006) is a good example to the contrary. Further implementations have to be investigated to uncover relevant factors that make interfaces particularly useful in the context of interactive, vection-based motion simulations.

4. Conclusions and outlook

The purpose of this study was to investigate various factors that may enhance illusions of self-motion in the context of lean, affordable and effective motion simulations. We chose factors that are relevant to current, interactive gaming and VR applications and can be implemented at little cost or effort. Turn velocity is a factor that may enhance vection for narrower turns as compared to wide turns (Trutoiu et al., 2009). We investigated turn velocity in contemporary 3D VR settings, because enhancing vection through narrow turns in the presented scene comes at almost no additional cost or purchase of equipment. Physical motion cueing seemed promising in the context of the vection literature, but only one attempt was found where these motion cues were integrated with a user interface in a simple and affordable fashion (Riecke, 2006). Because of the recent development of gaming chairs that embody both, user interaction and physical motion cues, we explored one of these devices with the hope that it may enhance vection at minimal cost and almost no effort to set up and maintain. User intervention and locomotion control is quite common in gaming and VR applications, but we did not find direct comparisons between passive vection and active vection that may help us identify factors important to the design of interactive motion simulators that leverage vection. We thus set out to investigate the factors turn velocity, physical motion cueing and interactivity and built a simple, reproducible VR system to test how these factors affect vection based on commonly used vection metrics such as vection intensity, latency and occurrence. In two psychophysics experiments, we exposed participants to conditions of straight paths, wide turns and narrow turns under conditions of physical motion cueing and locomotion control and recorded their responses during the experiment and in a post experiment interview. The following subsections conclude what we have found thus far in detail.

4.1. Turn velocity

In this study, we presented visual motion information in form of optic flow because optic flow is well represented in vection studies and commonly used, see Lowther & Ware (1996) or Trutoiu et al. (2009), for example. The optic flow motion stimulus was presented stereoscopically with correct perspective and FOV renderings based on head position. Binocular viewing and dynamic perspective renderings are becoming increasingly popular for VR applications and vection research because firstly, binocular cues may provide the user with additional motion information from inter-object disparity and inter-ocular velocity that may result in lower vection latency. Binocular vision may also help participants to separate the vection inducing background stimulus from the foreground which may facilitate vection (Palmisano, 1996, 2002). Additionally, stereoscopic display devices are now mainstream and commercially available in various forms such as 3D TVs so that the wide-spread adoption of this technology and its use to elicit vection is conceivable. Secondly, as evident in the vection literature, dynamically accounting for one's head motions in terms of the correct FOV and viewpoint rendering can reduce vection latency even in cases of linear forward vection (Lowther & Ware, 1996; Prothero & Parker, 2003). The associated tracking technology is already commercially available in form of camera based tracking systems used for gaming.

While previous studies showed that increasing turn velocities may facilitate vection under various presentation conditions such as naturalistic scenes in VR (Riecke & Schulte-Pelkum, 2006), physical mock-ups of rooms (Allison et al., 1999) and optokinetic drums (Dichgans & Brandt, 1978 Brandt et al., 1973), Trutoiu et al. (2009) directly compared linear and curvilinear trajectories in the context of vection using highly abstract optic flow and naturalistic scenes and found that curvilinear paths were more effective in eliciting vection compared to straight paths.

In the context of this study, we aimed to answer the following question: Does increasing turn velocity still facilitate vection based on optic flow under the aforementioned viewing conditions? To answer this question we exposed participants to curved (8°/s or 24°/s) and straight paths (0°/s) under conditions of 3D viewing and dynamic FOV/perspective renderings. We found that vection was rated as more intense, experienced earlier and more likely to occur for conditions of curved over straight paths

and that this effect was further pronounced for narrow turns (24°/s) compared to wider turns (8°/s).

As evident from this study (see section 3.2) along with findings across the vection literature, higher turn velocities seem to reliably and quite robustly improve the perception of illusory self-motion, regardless of the technology being used or the degree of “naturalness” of the visual motion stimulus (Allison et al., 1999; Brandt et al., 1973; Riecke, 2006; Riecke, Schulte-Pelkum, Avraamides, Heyde, & Bülthoff, 2006; Trutoiu et al., 2009; Wong & Frost, 1981). Despite stark differences in methods between the optokinetic drum used by Brandt et al. (1973) and the VR setup we used in our investigation, both studies show a similar, linear relationship between stimulus velocity and the perception of vection in terms of vection intensity estimates. While stereoscopic viewing conditions and dynamic perspective renderings may relatively enhance the overall self-motion experience, turn velocity still remains a predominant factor that determines vection.

Thus, whenever vection is desired for a given application, circular or curvilinear trajectories should be used because our findings and those of the vection literature, such as Trutoiu et al.(2009), indicate that curved paths are more effective in producing visually induced self-motion illusions over straight forward/backward paths. Additionally, Trutoiu mentioned that circular and curvilinear trajectories are structurally similar and thus similarly effective in eliciting visual vection. However, curvilinear trajectories inherently add a focus of expansion corresponding to the translation component which may yield additional motion information to the vection inducing stimulus (Trutoiu et al., 2009).

To enable natural self-motion simulation under conditions of various turn/straight path combinations, a few technical challenges have to be overcome. First off, Trutoiu highlights the importance of using floor projection to provide additional, lamellar flow in conjunction with wide FOV displays so that both, linear and curved paths can be effectively used to elicit visual vection (Trutoiu et al., 2009). Multi-display or projection setups require technical expertise and effort to setup and the adoption on a consumer level seems problematic. Secondly, current display technology is restricted to common refresh-rates of about 60Hz which limits the spatial information presented within a given

time (Riecke, Nusseck, & Schulte-Pelkum, 2006). This affects especially curved paths with turn velocities above 60 degrees per second. Blurring or color separation may occur which may adversely affect the user experience within the VE. Technological advancements seem necessary for VR systems to afford simple yet effective perceptions of more life-like and natural self-self-motion simulations.

4.2. Motion cueing

Free walking areas and motion platforms are commonly used to simulate self-motion in VR and to improve self-motion perception over traditional desktop-viewing environments. However, their implementation requires an usually high upfront cost of purchase, space, skilled personnel to setup and maintain, programming effort and safety precautions. The idea behind investigating affordable, physical motion cueing is to trigger a similar behavior in participants as if using free walking areas/motion platforms yet on less resources and potential of danger.

Simple motion cueing in the context of vection seems promising. Based on the vection literature, physical motion cueing concomittant to visually presented motion cues can facilitate vection under a vast variety of motion stimulus types. Evidence shows that this facilitation is observable in photorealistic VR (Schulte-Pelkum, 2007; Riecke, Schulte-Pelkum, & Caniard, 2006; Riecke, 2006) as well under traditional viewing conditions such as optokinetic drums (Wong & Frost, 1981). The facilitation particularly reduces vection latency and yields higher vection intensity estimates compared to conditions of no physical motion cueing. In some cases this effect can be quite noticeable considering the magnitude of physical motion cues used. For example, even relatively small physical jolts of about 1-3cm in the forward direction have shown to reduce vection latency by half for visually induced linear forward vection in VR (Riecke, Schulte-Pelkum, & Caniard, 2006).

Commonly, costly motion platforms (Riecke, Schulte-Pelkum, & Caniard, 2006; Wong & Frost, 1981) or modified, existing products (Riecke, 2006) have been used to generate or afford these physical motion cues. Our idea for this study was to provide physical motion cues “out-of-the-box” in order to test whether we can, in principle,

enhance the perception of self-motion for the average consumer. We thus aimed to extend aforementioned findings from the vection literature to an affordable-off the shelf input paradigm such as the Gyroxus gaming chair.

The Gyroxus gaming chair mapped forward/backward and right/left leaning motions of the user into velocity control for locomoting through VR. Both, vestibular and visual motion was qualitatively coupled so that chair motion almost immediately resulted in the corresponding, qualitative change in visual motion. This coupling of quality and timing between visual and vestibular motion was found to be critical in the context of vection (Riecke, Schulte-Pelkum, & Caniard, 2006; Riecke, 2006) and the Gyroxus motion paradigm seemed to afford this coupling on first sight.

To test whether the Gyroxus motion paradigm yielded beneficial vestibular cues in the context of vection, we seated participants on the chair and compared their vection experiences under 1) conditions of passive motion cueing where particiant were pushed in the chair vs. no motion cueing and 2) conditions of active motion cueing where participants applied motion cueing themselves vs. no motion cueing and just using a joystick to control locomotion (otherwise identical visual motion stimulus conditions).

Based on the Gyroxus paradigm we found, that motion cueing did enhance the experience of vection and extended these findings to 3D/dynamic FOV and perspective renderings in the context of optic flow (see subsection 3.3). Our findings suggest that participants experienced a heightened intensity of self-motion during conditions of physical motion cueing compared to conditions of no motion cueing.

Surprisingly, participants did not perceive vection earlier despite evidence in literature that motion cueing can fundamentally reduce vection latency (Riecke, Schulte-Pelkum, & Caniard, 2006). As such, motion cueing was not as influential as turn velocity on visual vection in the current study and we formulated some explanations for this effect:

Firstly, participants highlighted some technical issues with regards to the smoothness of the chair motions. Specifically, they noticed a jerk or mechanical blockage around the upright center position of the chair that distracted them and seemingly interrupted their experience. This mechanical blockage may have caused

conflict cues between visual and vestibular/somatosensory motion information in that the visual stimulus indicated forward motion and acceleration while the vestibular cues indicated a slowing down in instances when the chair had to overcome the mechanical blockage. These conflicting cues could have been responsible for the discomfort that participants reported during vection and possibly affected the perception of vection.

Secondly, participants may not have had access to the same visual motion information during physical motion cueing compared to conditions of no motion cueing due to the range-of-motion and the stereoscopic projection setup. The range-of-motion at the seating surface of the chair was only about 10cm in either direction parallel to the floor plane, but the torso and head could have moved by more than twice of that distance. Due to the motion paradigm of the Gyroxus, torso and head-motions could have occurred along an arch with the seat at its center and the torso and head as the radius. Despite the dynamic view frustrum, the visual motion stimulus may have been perceived differently at the limits of the range-of-motion compared to the center position. Particularly when polarized 3D display technology is used (such it was on our setup), one needs to ensure that participants have access to binocular information throughout their range-of-motion. If this is not provided, head orientation or location may be a confound in the context of vection research. To address this issue, we will upgrade our 3D projection system from linear to circular polarization to mitigate the possible break-down of stereoscopic information, particularly under conditions of head-tilt.

Thirdly, the experience of discomfort and motion sickness may have caused participants to behave differently as they normally would, regardless of their vection experience. Their altered state may have distracted them from reporting vection onset in a timely manner which could have unsystematically affected our data.

It seems that the above mentioned issues may be easily mitigated. Small body motions of a couple of centimeters seem enough to enhance vection. When properly implemented they can reduce the complexity of the setup in terms of calibrated tracking space, binocular vision and mechanical motion devices. Thus, we recommend the use of simple motion devices like the Gyroxus chair, but with a smaller range-of-motion and a sound mechanical structure that affords smooth and uniform motion profiles.

Overall, despite the poor implementation of the Gyroxus chair along with limitations of our setup, we were still able to find a beneficial effect of physical motion cueing on vection. This highlights the robustness of the effect under less than ideal circumstances with very affordable and easy to use hardware. The Gyroxus is compact and lightweight, with minimal safety concerns and little effort to set up. Based on this study and the vection literature, the approach of minimal, physical motion cueing shows a promising direction towards our ultimate goal of lean, elegant yet effective self-motion simulations.

4.3. Interactivity

Actively controlling locomotion through VR seems relevant in the context of current gaming and vehicle operator training scenarios. To the knowledge of the author, not much is known about the effects of interactivity in the context of vection.

Although care has to be taken when extrapolating these findings, evidence from related fields suggest that actively controlling self-motion may change our perception of the surround and provide additional, non-visual motion information. For example, Wexler et al. (2001) suggested that active observers perceive 3 dimensional structures differently compared to passive observers in that active observers have access to non-visual information that affects whether objects are merely perceived as rigid or embedded in an allocentric reference frame. If interactivity helps to establish an allocentric reference frame and thus the perception of vection, then implementing simple user interactions in VR could prove beneficial. As another example in the context of self-motion, Crowell et al. (1998) found that the perception of self-motion was more accurate when participants actively moved their head versus having their head passively moved. Their findings suggest that non-visual cues such as vestibular stimulation, neck proprioception and efferent motor commands may mediate perceptions of self-motion.

If actively controlling one's locomotion is beneficial to vection, how does it compare to passive locomotion? In the vection literature, passive (Berger et al., 2010; Schulte-Pelkum, 2007 [experiment 5]; Wong & Frost, 1981) and active (Riecke, 2006) motion cueing conditions have been investigated separately. To the best knowledge of

the author, however, there is no direct comparison between passive and active locomotion control in the vection literature. Findings across different studies can be difficult to compare because methods and stimulus conditions vary greatly. To close this gap, we investigated the effect active locomotion control versus passively experiencing locomotion through VR in the context of vection.

To test whether interactivity was beneficial to vection, we compared vection experiences between conditions of passively watching the visual motion stimulus vs. actively controlling locomotion using a joystick. To compare passive and active locomotion under conditions of physical motion cueing, we compared vection experiences between conditions where participants were passively pushed in the Gyroxus gaming chair and in conditions where participants applied motion cueing to the chair themselves to control their locomotion.

We found that vection latency was higher for active compared to passive conditions. Vection intensity was marginally higher for active locomotion over passive locomotion. Physical motion cueing did not seem to affect this trend.

Interestingly, actively controlling locomotion reduced the likelihood of vection occurrence for 8°/s turn velocity condition where otherwise no difference between active vs. passive conditions was noted. This effect disappeared for experiment 2 possibly due to familiarization.

Overall, the prolonged vection latency was more pronounced when participants used the Gyroxus chair to control locomotion than the joystick, but this effect vanished over time. In experiment 2, vection onset times were almost identical for both, joystick and chair and the difference between passive and active locomotion almost halved compared to experiment 1.

It seems clear that familiarization with both interfaces was the main factor affecting vection latency. Although the chair was novel, affected by technical issues and perceived as more difficult to use relative to the joystick, vection latency measures were not affected by interface device as much as by condition of interactivity once sufficient training time has passed.

It is not fully clear as to why participants took longer to perceive or report vection. We found two possible explanations for this effect: 1) Interactivity affects the perception of vection due to altered behavioral/viewing/fixation patterns or 2) Interactivity changes the behavior of participants so that they fail to observe or report their vection experience correctly thus biasing our data.

In context of vection literature, active locomotion may incur some sort of attentional load or preoccupation that could inhibit vection. For example, Seno, Ito, & Sunaga (2011) argued that if cognitive aspects such as the knowledge of the movability of a chair may facilitate or inhibit (in case of a non-moving chair) vection (Andersen & Braunstein, 1985), then there could be other cognitive factors that may inhibit vection, such as executing a task while experiencing visual vection. To test their idea, Seno and colleagues instructed participants to count the number of occurrences of letters that appeared in an luminance defined grating which was used to visually elicit vection. They introduced two levels of difficulty that differed in the frequency of the letters being presented and compared the treatment group with a control group that just passively watched the motion stimulus without executing the task. They found that vection onset time was larger for the difficult task compared to the control group, but not so for the low-frequency group compared to the control group. Their findings suggest that demanding cognitive tasks may reduce the induction of vection. These findings seem to be in line with observations from our study. Task difficulty may have been modulated by practice over time so that the cognitive load was only marginal during active locomotion once participants were sufficiently trained.

In conclusion, actively controlling locomotion did not benefit vection as initially expected. How we looked at interactivity and its effect on vection may need to be revised in the following sense: Instead of focusing on vection facilitation that may come about through actively controlling locomotion, we may need to look at mitigating vection reducing factors such as cognitive load that active locomotion control incurs. For example, we may consider designing input paradigms that are as user friendly and natural as possible and to give participants ample practice ahead of time.

4.4. Experiment 1 (training) vs. experiment 2 (main experiment)

Despite the fact that experiment 1 was merely a pretest and “burn-in” or training phase which made due with a third of trials compared to experiment 2, the findings were surprisingly consistent with those from experiment 2. As expected, the higher degree of training they received in experiment 1 yielded in generally more consistent responses in experiment 2 which reduced standard errors across the board, but particularly so for vection intensity. The following differences between the two experiments are noteworthy: The interaction effect between interactivity and turn velocity subsided for experiment 2 possibly through familiarization with the VR system. Additionally, significant differences between trajectories of 8°/s and 24°/s were detectable in experiment 2. Adding the straight path condition to the mix, it was not surprising that experiment 2 now showed a significant relationship between turn velocity and vection latency, although we lacked the sensitivity to detect any differences between 0°/s and 8°/s so that just 0°/s-24°/s comparisons were significant. In conclusion, even though both experiments showed the same trend, we deem it beneficial to include pre-tests and practice sessions such as experiment 1, especially when the setup is unknown or potentially cumbersome to participants.

4.5. Limitations

4.5.1. Internal validity

Despite attempts to reduce adverse effects of non-random patterns caused by group assignments, training effects, order effects and consistency in procedure (see subsection 2.4), there are some potential limitations worth mentioning. For both studies, the low number of participants (N = 24) and limited training time (about 15 minutes) could have been responsible for failures to detect more consistent effects of motion cueing and interactivity on vection occurrence and latency. For vection occurrence in particular, we had very few occurrences of no-vection cells as participants were generally able to experience vection in almost all trials. Our regression model had thus difficulty to detect any patterns in our data. In order to detect differences in the vection

latency metric, a more robust approach in form of physiological measures would have been helpful, but vection is an introspective phenomenon after all and physiological measures are not reliable enough yet.

Additionally, the setup and procedure may need improvement in the way motion/no motion cueing and interactivity conditions are administered. For chair motions, the Gyroxus had to be physically unlocked and mechanically locked for no motion cueing conditions which would have introduced too much overhead to fully randomize conditions. An automated interlocking mechanism on the chair would have allowed us to further reduce order effects and use a more powerful statistical model. However, the design and implementation of such mechanism was not feasible given the allotted resources.

Individually experienced differences in the methodology and procedure may have affected the study outcome. Theoretically, every participant should have experienced the same conditions due to the automated, computer directed script that experimenter and participant followed. In practice, however, participants experienced the study slightly different. For example, participants were exposed to a number of training trials based on their ability to control the chair and joystick. If participants did well, they continued to the experimental phase after a couple training trials but if they experienced difficulty, they spend up to 10 times more on training than others. The goal behind establishing a training criterion was to ensure that all participants were able to precisely follow the computer animated follow-me object. This skill was crucial for experiment design because their ability to follow the follow-me object determined the discrepancy of trajectories and thus visual motion information between active and passive locomotion conditions. Even though this practice was necessary for the experiment, it could have lead to frustrations and effects of motion sickness in participants and possibly biased their responses.

Response bias could also have been an issue during the informal post experimental interview where questions were presented in a fixed, non-random order. Last but not least and despite best practices, we cannot exclude the possibility that participants may have just falsely reported their experiences.

4.5.2. External validity

We are aware that our participant base limited the generalisability of this study as we ran experiments on physically unchallenged, young persons who were generally computer and 3D computer game savvy. Our participant base was sampled through various channels (see subsection 2.1) and we offered financial reimbursement to attract a broad variety of participants outside the SFU Surrey campus as well. However, despite our attempts to attract a wider demographic, we found that more young adult males (62.5%) than females signed up for the study, most of which had or were in the process of obtaining a university degree (70.8%). From that limited sample we then had to exclude participants that did not perceive vection or who experienced severe vection drop-outs early on during the experiments (14.3%).

4.5.3. Application of vection on a consumer level

In a laboratory setting that provides resources and talent to setup virtually any VR system for research purposes it is possible to create rich and engaging virtual worlds with cutting edge technology. However, the challenges that can be addressed through technology and custom implementations may continue to exist for the average consumer. Even though “immersive” display technology and embodied interface devices become more affordable and available, their working together in harmony and their software support especially for interactive applications still remain a problem. That is, users may face difficulty to write a program for their computer games to work with their gaming chair, support 3D renderings and dynamic perspective renderings that in turn call for an integration of some sort of tracking mechanism. While the technology is available in its components, a complete product may be difficult to find. To date, vection in passive and stationary observer seem more likely in the context of 3D movie titles and widely available playback and display devices for the average living room.

4.6. Future directions

In essence, the discourse in this paper and our investigation show that vection can be enhanced with little effort. That is, physical changes to the setup may not be necessary, as merely adding narrow turns to the simulation seem to be highly effective

in the context of vection. Small changes to the setup that afford minimal user motions may be quite robust in enhancing the user experience. If users are unfamiliar with the system, its effectiveness in eliciting vection may be maintained after short training phase on the system even if the implementations is suboptimal. From our research it becomes obvious that less is sometimes more and we thus aim our future research focus towards enhancing vection experiences and ways to measure them within these fairly simple and affordable vection-inducing virtual reality systems. Below, we have identified relevant and closely related research topics that we are planning to address.

4.6.1. Re-design for the Gyroxus motion paradigm

Using the affordable, off-the-shelf Gyroxus chair to afford physical motion cueing has shown promising results and a step towards lean self-motion simulation. What primarily attracted us to the Gyroxus was the full body motion paradigm where the feet are off the ground and the footrest along with the seat suspended on tension wires. Suspending the body in a similar manner has shown to facilitate vection (Riecke et al., 2009), partially because of cognitive factors and partially because of the cross-modal benefit that the relatively free body motions may afford.

However, the Gyroxus had drawbacks that turned out to be problematic for our vection study. Firstly, the chair did not have a re-centering force. Participants thus had to put effort into going back to a “zero” position. This is very unintuitive as most common desktop velocity control interfaces are expected to return to a default state when the force applied to them is released (i.e., key press, button press or joystick handle). Participants often overcompensated when attempting to re-center which then resulted in an exaggerated compensatory motion in the opposite direction. The result was an oscillation with decreasing amplitude until the center position was finally found. Secondly, the range-of-motion of the chair was quite large compared to small joggles or “jerks” previously mentioned in the vection literature (Riecke, 2006; Riecke et al., 2009; Schulte-Pelkum, 2007). In context of the Gyroxus chair, the greater the leaning motion, the more difficult it was to leave one’s current position and move to another position due to the gravitational forces/body weight that participants had to overcome at greater tilt angles. Thirdly, the sensitivity of the chair may have been too high. We adjusted the maximum velocity to be about twice as high compared to the cube velocity at maximum

chair deflection so that participants could “catch up” to the cube in case they fell behind. It seems that the lack of control over the chair motions in conjunction with this velocity/displacement mapping was less-than-ideal. Finally, the chair was plagued with reliability issues. Shortly after the built-in tracking mechanism failed, the mechanical linkage guiding the chair motions on its suspension wires started to seize up intermittently just around the center position which may have exacerbated the overcompensating user inputs on the chair.

We learned from our experiences using the Gyroxus chair that these types of input devices should afford accurate control over the deflection of the seating surface within the available range-of-motion without great effort. An improvement of the existing implementation would be

1) A re-centering force that may help participants to get back to a known and neutral state so that they don’t have to actively find it. This aspect may reduce the effort they invest in controlling their locomotion especially when they are not very familiar with the device.

2) The use of small, smooth and easy to control motions that are less effortful and keep participants from fighting against their own weight during body adjustments. Additionally, a small range-of-motion may keep the mechanical implementation of the interface less complicated.

3) A more solid seating platform as the plastics and structure used for the Gyroxus gaming chair flexed and wore considerably in the short time we have used it.

4) Optimized mapping between the device range-of-motion and visual velocity to give participants the best level of locomotion control.

As a consequence of the above stated recommendations, we are currently investigating the Gyroxus motion paradigm based on a Swopper chair for our VR system that can be used much like the Gyroxus through body tilts, but it additionally affords turning in place, similar to an office chair. The solid, cast-iron base of the chair and its gas-spring suspension seem to be resilient enough for long-term use and the chair’s design allows for flexibility for future modifications. In the context of VR interface

devices, the Swopper has already made its appearance as locomotion control paradigm in a first-person shooter application (Beckhaus, Blom, & Haringer, 2005). The Swopper seems promising in addressing the shortcoming of the Gyroxus chair although custom modifications are necessary to convert this ergonomic office chair into a VR interface.

4.6.2. Electroencephalography (EEG) to corroborate introspective vection measures

From our experiments it was not clear whether actively controlling locomotion directly affected experiences of vection or if participants failed to report aspects of vection (vection latency in particular) correctly, or both. To help disambiguate between those two cases, a combination of introspective, qualitative and physiological measures may help us to more accurately triangulate the experience of vection. In a highly experimental investigation, we are examining the role of consumer grade EEG devices such as the Emotive EPOC system to capture neurological activity for pattern analysis in the context of vection. The idea behind these physiological measures is to correlate EEG patterns with introspective and qualitative data to get a more complete picture of the quality and timing of the vection experience.

4.6.3. Mitigating motion sickness through active locomotion

It is believed that when a person actively controls a moving vehicle he is less likely to experience motion sickness compared to when he is passively being transported in the same vehicle. A possible explanation of this effect is the relationship between motor efference copies and visuo-vestibular afference in that the perceptual system may be somewhat primed for the motion stimulus ahead of time in conditions where the user controls his own locomotion (Rolnick & Lubow, 1991). For example, Rolnick & Lubow (1991) exposed a pair of two participants to circular motion on a rotating platform. Both participants sat next to each other, but only one controlled their direction, acceleration, velocity and deceleration on the platform through a joystick. To ensure that all other factors were held identical for both observers, the participant who did not control the rotations was instructed to use a dummy joystick identical to the one used to control the platfrom as if he was controlling the motion. The study showed that 11.4 % of the participants who were passively exposed to the motion stimulus had to prematurely

abort the experiments due to severe motion sickness whereas only 4% did so when actively controlling their locomotion. Overall, actively controlling resulted in a less pronounced development of motion sickness over time compared to passive motion exposure. We are revisiting the hypothesis of Rolnick & Lubow (1991) in the context of vection in an immersive VR setup using various locomotion control paradigms, such as the Swopper or a modified hammock chair as well as a traditional joystick and keyboard. Our goal is to find specific circumstances in which motion sickness is mitigated when participants actively or passively control their locomotion in the context of vection.

References

Agaeva, M. Y., & Altman, Y. A. (2005). Effect of a Sound Stimulus on Postural Reactions. *Human Physiology*, *31*(5), 511–514. doi:10.1007/s10747-005-0090-4

Allison, R. S., Howard, I. P., & Zacher, J. E. (1999). Effect of field size, head motion, and rotational velocity on roll vection and illusory self-tilt in a tumbling room. *Perception*, *28*, 299–306.

Andersen, G. J., & Braunstein, M. L. (1985). Induced Self-Motion in Central Vision. *Journal of Experimental Psychology – Human Perception and Performance*, *11*(2), 122–132.

Atkins, R. (2008). Enhance virtual reality - Engineering Challenges. Retrieved June 21, 2013, from http://www.engineeringchallenges.org/cms/8996/9140.aspx

Baumgartner, T., Valko, L., Esslen, M., & Jäncke, L. (2006). Neural correlate of spatial presence in an arousing and noninteractive virtual reality: an EEG and psychophysiology study. *CyberPsychology & Behavior*, *9*(1), 30–45.

Becker, W., Raab, S., & Jürgens, R. (2002). Circular vection during voluntary suppression of optokinetic reflex. *Experimental Brain Research*, *144*(4), 554–557.

Beckhaus, S., Blom, K. J., & Haringer, M. (2005). A new gaming device and interaction method for a First-Person-Shooter. *Proceedings of the Computer Science and Magic*, *2005*.

Berger, D. R., Schulte-Pelkum, J., & Bülthoff, H. H. (2010). Simulating believable forward accelerations on a stewart motion platform. *ACM Trans. Appl. Percept.*, *7*(1), 5:1–5:27. doi:10.1145/1658349.1658354

Berthoz, A., & Droulez, J. (1982). Linear self motion perception. In A. H. Wertheim, W. A. Wagenaar, & H. W. Leibowitz (Eds.), *Tutorials on Motion Perception* (pp. 157–199). New York: Plenum.

Berthoz, A., Pavard, B., & Young, L. R. (1975). Perception of linear horizontal self-motion induced by peripheral vision (linearvection) basic characteristics and visual-vestibular interactions. *Experimental Brain Research*, *23*(5), 471–489. doi:10.1007/BF00234916

Brandt, T., Bartenstein, P., Janek, A., & Dieterich, M. (1998). Reciprocal inhibitory visual-vestibular interaction - Visual motion stimulation deactivates the parieto-insular vestibular cortex. *Brain*, *121*, 1749–1758.

Brandt, T., Dichgans, J., & Koenig, E. (1973). Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research*, *16*(5), 476–491. doi:10.1007/BF00234474

Brandt, T., Wist, E. R., & Dichgans, J. (1975). Foreground and Background in Dynamic Spatial Orientation. *Perception & Psychophysics*, *17*(5), 497–503.

Bremmer, F., & Lappe, M. (1999). The use of optical velocities for distance discrimination and reproduction during visually simulated self motion. *Exp. Brain Res.*, *127*(1), 33–42.

Bremmer, Frank. (2005). Navigation in space – the role of the macaque ventral intraparietal area. *The Journal of Physiology*, *566*(1), 29–35. doi:10.1113/jphysiol.2005.082552

Cheung, Bob, Hofer, K., Heskin, R., & Smith, A. (2004). Physiological and behavioral responses to an exposure of pitch illusion in the simulator. *Aviation, space, and environmental medicine*, *75*(8), 657–665.

Cheung, BS, Howard, I., & Money, K. (1991). Visually-induced sickness in normal and bilaterally labyrinthine-defective subjects. *Aviation, space, and environmental medicine*, *62*(6), 527–531.

Cowings, P. S. (1990). Autogenic-feedback training: A treatment for motion and space sickness. *Motion and space sickness*, 353–372.

Crampton, G. H., & Young, F. A. (1953). The differential effect of a rotary visual field on susceptibles and nonsusceptibles to motion sickness. *Journal of comparative and physiological psychology*, *46*(6), 451.

Crowell, J. A., Banks, M. S., Shenoy, K. V., & Andersen, R. A. (1998). Visual self-motion perception during head turns. *Nat. Neurosci.*, *1*(8), 732–737.

Dichgans, J., & Brandt, T. (1978). Visual-Vestibular Interaction: Effects on Self-Motion Perception and Postural Control. In *Perception* (Vol. VIII, pp. 756–804). Springer.

Diener, H. C., Wist, E. R., Dichgans, J., & Brandt, T. (1976). The spatial frequency effect on perceived velocity. *Vision Research*, *16*(2), 169–IN7. doi:10.1016/0042-6989(76)90094-8

Dieterich, M., Bense, S., Stephan, T., Yousry, T., & Brandt, T. (2003). fMRI signal increases and decreases in cortical areas during small-field optokinetic stimulation and central fixation. *Experimental Brain Research*, *148*(1), 117–127. doi:10.1007/s00221-002-1267-6

Durgin, F. H., Pelah, A., Fox, L. F., Lewis, J. Y., Kane, R., & Walley, K. A. (2005). Self-Motion Perception During Locomotor Recalibration: More than Meets the Eye. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(3), 398–419.

Fang, L., & Loughin, T. M. (2012). Analyzing Binomial Data in a Split-Plot Design: Classical Approach or Modern Techniques? *Communications in Statistics - Simulation and Computation*, *42*(4), 727–740. doi:10.1080/03610918.2011.650264

Fischer, M. H., & Kornmüller, A. E. (1930). Optokinetisch ausgelöste Bewegungswahrnehmung und optokinetischer Nystagmus [Optokinetically induced motion perception and optokinetic nystagmus]. *Journal für Psychologie und Neurologie*, 273–308.

Flanagan, M. B., May, J. G., & Dobie, T. G. (2004). The role of vection, eye movements and postural instability in the etiology of motion sickness. *Journal of Vestibular Research-Equilibrium & Orientation*, *14*(4), 335–346.

Fushiki, H., Takata, S., & Watanabe, Y. (2000). Influence of fixation on circular vection. *Journal of Vestibular Research-Equilibrium & Orientation*, *10*(3), 151–155.

Ghahramani, Z., Wolpert, D. M., & Michale I., J. (1997). Computational models of sensorimotor integration. In Pietro Morasso and Vittorio Sanguineti (Ed.), *Advances in Psychology* (Vol. Volume 119, pp. 117–147). North-Holland. Retrieved from http://www.sciencedirect.com/science/article/pii/S0166411597800064

Ghazanfar, A. A., & Schroeder, C. E. (2006). Is neocortex essentially multisensory? *Trends in Cognitive Sciences*, *10*(6), 278–285. doi:10.1016/j.tics.2006.04.008

Giannopulu, I., & Lepecq, J.-C. (1998). Linear-vection chronometry along spinal and sagittal axes in erect man. *Perception, London*, *27*, 363–372.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Houghton Mifflin, Boston.

Gibson, James J. (1954). The visual perception of objective motion and subjective movement. *Psychological Review*, *61*(5), 304–314.

Gibson, James J. (1966). The senses considered as perceptual systems.

Gibson, James J. (2002). A theory of direct visual perception. *Vision and mind: Selected readings in the philosophy of perception*, 77–89.

Gregory, R. L. (1970). The intelligent eye.

Gregory, R. L. (1974). *Concepts and mechanisms of perception*. Duckworth London.

Harm, D. L. (1990). Physiology of motion sickness symptoms. *Motion and space sickness*, 154–177.

Havron, M. D., & Butler, L. F. (1957). Evaluation of training effectiveness of the 2FH2 helicopter flight trainer research tool. *Naval Training Device Center, Port Washington, NY*.

Helmholtz, H. von. (1867). *Handbuch der physiologischen Optik*. Leipzig: Voss.

Helmholtz, H. von. (1896). *Handbuch der physiologischen Optik*. Hamburg-Leipzig: L. Voss.

Hettinger, L. J. (2002). Illusory Self-motion in Virtual Environments. In K. M. Stanney (Ed.), *Handbook of Virtual Environments* (pp. 471–492). Lawrence Erlbaum.

Hettinger, Lawrence J., Berbaum, K. S., Kennedy, R. S., Dunlap, W. P., & Nolan, M. D. (1990). Vection and Simulator Sickness. *Military Psychology*, *2*(3), 171.

Howard, I. P. (1982). *Human visual orientation*. Chichester, New York, Engl.: J. Wiley.

Howard, I. P. (1986a). The perception of posture, self motion, and the visual vertical. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Sensory processes and perception* (Vol. 1, pp. 18.1–18.62). New York: John Wiley & Sons.

Howard, I. P. (1986b). The vestibular system. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Sensory processes and perception* (Vol. 1, pp. 11.1–11.30). New York: Wiley.

Howard, I. P., & Howard, A. (1994). Vection - the contributions of absolute and relative visual motion. *Perception*, *23*(7), 745–751.

Hu, S., Grant, W., Stern, R., & Koch, K. (1991). Motion sickness severity and physiological correlates during repeated exposures to a rotating optokinetic drum. *Aviation, space, and environmental medicine*, *62*(4), 308–314.

Hu, S., Stritzel, R., Chandler, A., & Stern, R. (1995). P6 acupressure reduces symptoms of vection-induced motion sickness. *Aviation, space, and environmental medicine*, *66*(7), 631–634.

Irwin, J. A. (1881). The pathology of sea-sickness. *The Lancet*, *118*(3039), 907–909.

Johnson, W. H., Sunahara, F. A., & Landolt, J. P. (1999). Importance of the vestibular system in visually induced nausea and self-vection. *Journal of Vestibular Research*, *9*(2), 83–87.

Jokerst, M., Gatto, M., Fazio, R., Stern, R., & Koch, K. (1999). Slow deep breathing prevents the development of tachygastria and symptoms of motion sickness. *Aviation, space, and environmental medicine*, *70*(12), 1189–1192.

Jozsvai, E., & Pigeau, R. (1996). The effect of autogenic training and biofeedback on motion sickness tolerance. *Aviation, space, and environmental medicine*, *67*(10), 963–968.

Kapteyn, T. S., & Bles, W. (1977). Circular Vection and Human Posture .3. Relation Between Reactions to Various Stimuli. *Agressologie*, *18*(6), 335–339.

Kennedy, R. S. (1996). Postural instability induced by virtual reality exposure: Development of a certification protocol. *International journal of human-computer interaction*, *8*(1), 25.

Kennedy, R. S., Berbaum, K. S., & Lilienthal, M. G. (1997). *Disorientation and postural ataxia following flight simulation* (Vol. 68). Alexandria, VA, United States. Aerospace Medical Association.

Kennedy, R. S., Hettinger, L. J., Harm, D. L., Ordy, J. M., & Dunlap, W. P. (1996). Psychophysical scaling of circular vection (CV) produced by optokinetic (OKN) motion: Individual differences and effects of practice. *Journal of Vestibular Research-Equilibrium & Orientation*, *6*(5), 331–341.

Kennedy, Robert S., Drexler, J., & Kennedy, R. C. (2010). Research in visually induced motion sickness. *Special Section - The First International Symposium on Visually Induced Motion Sickness, Fatigue, and Photosensitive Epileptic Seizures (VIMS2007)*, *41*(4), 494–503. doi:10.1016/j.apergo.2009.11.006

Khasnis, A., & Gokula, R. M. (2003). Romberg's test. *J Postgrad Med*, *49*(2), 169–172.

Lackner, J. R. (1977). Induction of Illusory Self-Rotation and Nystagmus by a Rotating Sound-Field. *Aviation Space and Environmental Medicine*, *48*(2), 129–131.

Lackner, James R, & Teixeira, R. (1977). Optokinetic motion sickness: continuous head movements attenuate the visual induction of apparent self-rotation and symptoms of motion sickness. *Aviation, space, and environmental medicine*, *48*(3), 248.

Lawson, B. D., Graeber, D. A., Mead, A. M., & Muth, E. R. (2002). Signs and Symptoms of Human Syndromes associated with Synthetic Experiences. In K. M. Stanney (Ed.), *Handbook of Virtual Environments* (pp. 589–618). Lawrence Erlbaum.

Lawson, B. D., Sides, S. A., & Hickinbotham, K. A. (2002). User Requirements for Perceiving Body Acceleration. In K. M. Stanney (Ed.), *Handbook of Virtual Environments* (pp. 135–161). Lawrence Erlbaum.

Lepecq, J. C., Giannopulu, I., & Baudonniere, P. M. (1995). Cognitive effects on visually induced body motion in children. *Perception*, *24*(4), 435–449.

Lepecq, J. C., Giannopulu, I., Mertz, S., & Baudonniere, P. M. (1999). Vestibular Sensitivity and Vection Chronometry Along the Spinal Axis in Erect man. *Perception*, *28*(1), 63–72.

Lepecq, J. C., Jouen, F., & Dubon, D. (1993). The Effect of Linear Vection on Manual Aiming at Memorized Directions of Stationary Targets. *Perception*, *22*(1), 49–60.

Lestienne, F., Soechting, J., & Berthoz, A. (1977). Postural Readjustments Induced by Linear Motion of Visual Scenes. *Experimental Brain Research*, *28*(3-4), 363–384.

Lishman, J. R. (1973). Autonomy of Visual Kinaesthesis. *Perception*, *2*(3), 287–294.

Lowther, K., & Ware, C. (1996). Vection with large screen 3D imagery. In *Conference Companion on Human Factors in Computing Systems* (pp. 233–234). New York, NY, USA: ACM. doi:10.1145/257089.257297

Mach, E. (1875). *Grundlinien der Lehre von der Bewegungsempfindung*. Leipzig, Germany: Engelmann.

Marmekarelse, A. M., & Bles, W. (1977). Circular vection and human posture II: Does the auditory-system play a role. *Agressologie*, *18*(6), 329–333.

McCauley, M., & Sharkey, T. J. (1992). Cybersickness- Perception of self-motion in virtual environments. *Presence: Teleoperators and Virtual Environments*, *1*(3), 311–318.

Mergner, T., & Rosemeier, T. (1998). Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions—a conceptual model. *Brain Research Reviews*, *28*(1–2), 118–135. doi:10.1016/S0165-0173(98)00032-0

Mittelstaedt, M.-L., & Mittelstaedt, H. (2001). Idiothetic navigation in humans: estimation of path length. *Experimental Brain Research*, *139*(3), 318–332. doi:10.1007/s002210100735

Ohmi, M., & Howard, I. P. (1988). Effect of Stationary Objects on Illusory Forward Self-Motion Induced by a Looming Display. *Perception*, *17*(1), 5–11.

Ohmi, M., Howard, I. P., & Landolt, J. P. (1987). Circular Vection as a Function of Foreground-Background Relationships. *Perception*, *16*(1), 17–22.

Palmisano, S. (1996). Perceiving self-motion in depth: The role of stereoscopic motion and changing-size cues. *Perception & Psychophysics*, *58*(8), 1168–1176.

Palmisano, S. (2002). Consistent stereoscopic information increases the perceived speed of vection in depth. *Perception*, *31*(4), 463–480.

Prothero, J. D., & Parker, D. E. (2003). A unified approach to presence and motion sickness. *Virtual and Adaptive Environments: Applications, Implications, and Human Performance Issues*, 47–66.

Reason, J. (1978). Motion sickness: Some theoretical and practical considerations. *Applied Ergonomics*, *9*(3), 163–167. doi:10.1016/0003-6870(78)90008-X

Reason, J. T., & Brandt, J. J. (1975). *Motion Sickness.* London: Academic Press.

Riccio, G. E., & Stoffregen, T. A. (1991). An ecological Theory of Motion Sickness and Postural Instability. *Ecological Psychology*, *3*(3), 195.

Richards, J. T., Mulavara, A. P., & Bloomberg, J. J. (2004). Postural Stability During Treadmill Locomotion as a Function of the Visual Polarity and Rotation of a Three-Dimensional Virtual Environment. *Presence: Teleoperators and Virtual Environments*, *13*(3), 371–384. doi:10.1162/1054746041422299

Riecke, B. E. (2006). Simple user-generated motion cueing can enhance self-motion perception (Vection) in virtual reality. In *Proceedings of the ACM symposium on Virtual reality software and technology* (pp. 104–107).

Riecke, B. E, Schulte-Pelkum, J., Caniard, F., & Bulthoff, H. H. (2005). Towards lean and elegant self-motion simulation in virtual reality. *IEEE Virtual Reality, 2005. Proceedings. VR 2005*, 131–138.

Riecke, B. E. (2009). Cognitive and higher-level contributions to illusory self-motion perception (“vection”): does the possibility of actual motion affect vection? *Japanese Journal of Psychonomic Science*, *28*(1), 135–139.

Riecke, B. E., & Heyde, M. von der. (2002). *Qualitative Modeling of Spatial Orientation Processes using Logical Propositions: Interconnecting Spatial Presence, Spatial Updating, Piloting, and Spatial Cognition* (No. 100). MPI for Biological Cybernetics.

Riecke, B. E., & McNamara, T. P. (2007). Spatial Orientation in the Immediate Environment: How Can the Different Theories be Reconciled? In H. H. Bülthoff, H. A. Mallot, R. Ulrich, & F. A. Wichmann (Eds.), *10. Tübingen Perception Conference (TWK)*. Max Planck Institute for Biological Cybernetics, Germany: Knirsch Verlag, Kirchentellinsfurt, Germany. Retrieved from http://twk.tuebingen.mpg.de/twk07/abstract.php?_load_id=riecke01

Riecke, B. E., Nusseck, H.-G., & Schulte-Pelkum, J. (2006). *Selected Technical and Perceptual Aspects of Virtual Reality Displays* (No. 154). MPI for Biological Cybernetics. Retrieved from http://www.kyb.mpg.de/publication.html?publ=4188

Riecke, B. E., & Schulte-Pelkum, J. (2006). *Using the perceptually oriented approach to optimize spatial presence & ego-motion simulation* (No. 153). MPI for Biological Cybernetics. Retrieved from http://www.kyb.mpg.de/publication.html?publ=4186

Riecke, B. E., Schulte-Pelkum, J., Avraamides, M. N., Heyde, M. von der, & Bülthoff, H. H. (2006). Cognitive Factors can Influence Self-Motion Perception (Vection) in Virtual Reality. *ACM Transactions on Applied Perception*, *3*(3), 194–216. doi:http://doi.acm.org/10.1145/1166087.1166091

Riecke, B. E., Schulte-Pelkum, J., & Caniard, F. (2006). Visually induced linear vection is enhanced by small physical accelerations. In *7th International Multisensory Research Forum (IMRF)*. Dublin, Ireland. Retrieved from http://www.kyb.mpg.de/publication.html?publ=3901

Riecke, B. E., Feuereissen, D., & Rieser, J. J. (2009). Auditory self-motion simulation is facilitated by haptic and vibrational cues suggesting the possibility of actual motion. *ACM Transactions on Applied Perception (TAP)*, *6*, 20:1–20:22. doi:http://doi.acm.org/10.1145/1577755.1577763

Riecke, B. E., Feuereissen, D., & Rieser, J. J. (2010). Spatialized sound influences biomechanical self-motion illusion ("vection"). In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization* (pp. 158–158). doi:10.1145/1836248.1836280

Riecke, B. E., Feuereissen, D., Rieser, J. J., & McNamara, T. P. (2012). Self-Motion Illusions (Vection) in VR – Are They Good For Anything? In *IEEE Virtual Reality 2012* (pp. 35–38). Orange County, CA, USA. doi:10.1109/VR.2012.6180875

Riecke, B. E., Schulte-Pelkum, J., Avraamides, M. N., Heyde, M. V. D., & Bülthoff, H. H. (2006). Cognitive factors can influence self-motion perception (vection) in virtual reality. *ACM Trans. Appl. Percept.*, *3*(3), 194–216. doi:10.1145/1166087.1166091

Riecke, B. E., Väljamäe, A., & Schulte-Pelkum, J. (2009). Moving sounds enhance the visually-induced self-motion illusion (circular vection) in virtual reality. *ACM Transactions on Applied Perception*, *6*(2), 1–27. doi:10.1145/1498700.1498701

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*(6), 1157–1165.

Rolnick, A., & Lubow, R. E. (1991). Why is the driver rarely motion sick? The role of controllability in motion sickness. *Ergonomics*, *34*(7), 867–879. doi:10.1080/00140139108964831

Sato, T., Seno, T., Kanaya, H., & Fukazawa, H. (2007). Dominance of ground stimuli in vection induction. *Perception*, *36*, 180–181.

Schaffer, E. S., & Durgin, F. H. (2005). Visual-vestibular dissociation: Differential sensitivity to acceleration and velocity. *Journal of Vision*, *5*(8), 332–332.

Schulte-Pelkum, J. (2007). *Perception of self-motion: Vection experiments in multi-sensory Virtual Environments* (PhD thesis). Ruhr-Universität Bochum.

Schulte-Pelkum, J., Riecke, B. E., & Bülthoff, H. H. (2004). Vibrational cues enhance believability of ego-motion simulation. In *International Multisensory Research Forum (IMRF)*. Retrieved from http://www.kyb.mpg.de/publication.html?publ=2766

Schulte-Pelkum, J., Riecke, B. E., von der Heyde, M., & Bülthoff, H. H. (2003). Circular vection is facilitated by a consistent photorealistic scene. *Proceedings of Presence 2003*.

Seno, T., Ito, H., & Sunaga, S. (2009). The object and background hypothesis for vection. *Vision Research*, *49*(24), 2973 – 2982. doi:10.1016/j.visres.2009.09.017

Seno, T., Ito, H., & Sunaga, S. (2011). Attentional load inhibits vection. *Attention, Perception, & Psychophysics*, *73*(5), 1467–1476. doi:10.3758/s13414-011-0129-3

Soto-Faraco, S., Spence, C., Lloyd, D., & Kingstone, A. (2004). Moving Multisensory Research Along: Motion Perception Across Sensory Modalities. *Current Directions in Psychological Science*, *13*(1), 29–32.

Soto-Faraco, Salvador, Kingstone, A., & Spence, C. (2003). Multisensory contributions to the perception of motion. *Neuropsychologia*, *41*(13), 1847–1862.

Stanney, K. M., Kennedy, R. S., Drexler, J. M., & Harm, D. L. (1999). Motion sickness and proprioceptive aftereffects following virtual environment exposure. *Applied Ergonomics*, *30*(1), 27–38. doi:10.1016/S0003-6870(98)00039-8

Stern, R., Koch, K., Stewart, W., & Lindblad, I. (1987). Spectral analysis of tachygastria recorded during motion sickness. *Gastroenterology*, *92*(1), 92–97.

Stern, R. M., Koch, K. L., Stewart, W. R., & Vasey, M. W. (1987). Electrogastrography: Current Issues in Validation and Methodology. *Psychophysiology*, *24*(1), 55–64. doi:10.1111/j.1469-8986.1987.tb01862.x

Stevens, S. S. (1957). On the psychophysical Law. *Psychological Review*, *64*(3), 153–181.

Stoffregen, T. A., & Riccio, G. E. (1991). An Ecological Critique of the Sensory Conflict Theory of Motion Sickness. *Ecological Psychology*, *3*(3), 159.

Sun, H. J., Campos, J. L., Young, M., Chan, G. S. W., & Ellard, C. G. (2004). The contributions of static visual cues, nonvisual cues, and optic flow in distance estimation. *Perception*, *33*(1), 49–65.

Tokumaru, O., Kaida, K., Ashida, H., Yoneda, I., & Tatsuno, J. (1999). EEG topographical analysis of spatial disorientation. *Aviation, space, and environmental medicine*, *70*(3), 256–263.

Trutoiu, L. C., Mohler, B. J., Schulte-Pelkum, J., & Bülthoff, H. H. (2009). Circular, linear, and curvilinear vection in a large-screen virtual environment with floor projection. *Computers & Graphics*, *33*(1), 47–58. doi:10.1016/j.cag.2008.11.008

Trutoiu, L. C., Streuber, S., Mohler, B. J., Schulte-Pelkum, J., & Bülthoff, H. H. (2008). Tricking people into feeling like they are moving when they are not paying attention. In *Proceedings of the 5th symposium on Applied perception in graphics and visualization* (pp. 190–190). New York, NY, USA: ACM. doi:10.1145/1394281.1394319

Tschermak, A. (1931). Optischer Raumsinn. In A. Bethe, G. Bergmann, G. Embden, & A. Ellinger (Eds.), *Handbuch der Normalen und Pathologischen Physiologie* (pp. 834–1000). Springer, Berlin.

Tulving, E., & Schacter, D. L. (1990). Priming and human memory systems. *Science*, *247*(4940), 301–306.

Uijtdehaage, S. H., Stern, R. M., & Koch, K. L. (1992). Effects of Eating on Vection-Induced Motion Sickness, Cardiac Vagal Tone, and Gastric Myoelectric Activity. *Psychophysiology*, *29*(2), 193–201.

Väljamäe, A. (2009). Auditorily-induced illusory self-motion: A review. *Brain Research Reviews*, *61*(2), 240 – 255. doi:10.1016/j.brainresrev.2009.07.001

Van der Steen, F. A. M. (1996). Simulating self-motion. *Brain Research Bulletin*, *40*(5–6), 473 – 475. doi:10.1016/0361-9230(96)00144-X

Warren, R., & Wertheim, A. H. (1990). *Perception & Control of Self Motion*. Erlbaum, Hillsdale, NJ.

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nat. Neurosci.*, *4*(2), 213–216.

Wexler, M., Panerai, F., Lamouret, I., & Droulez, J. (2001). Self-motion and the perception of stationary objects. *Nature*, *409*(6816), 85–88. doi:10.1038/35051081

Wiener, S. I., Berthoz, A., & Zugaro, M. B. (2002). Multisensory processing in the elaboration of place and head direction responses by limbic system neurons. *Multisensory Proceedings*, *14*(1), 75–90. doi:10.1016/S0926-6410(02)00062-9

Wist, E. R., Diener, H. C., Dichgans, J., & Brandt, T. (1975). Perceived distance and perceived speed of self-motion - linear vs angular velocity. *Perception & Psychophysics*, *17*(6), 549–554.

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, *269*(5232), 1880–1882.

Wong, S. C. P., & Frost, B. J. (1981). The effect of visual-vestibular conflict on the latency of steady-state visually induced subjective rotation. *Perception & Psychophysics*, *30*(3), 228–236.

Wood, R. W. (1895). The “Haunted Swing” illusion. *Psychological Review*, *2/3*, 277–278.

Wright, W. G., DiZio, P., & Lackner, J. R. (2006). Perceived self-motion in two visual contexts: Dissociable mechanisms underlie perception. *Journal of Vestibular Research: Equilibrium & Orientation*, *16*(1/2), 23–28.

Appendices

Appendix A: Consent and instructions

Informed consent form

Informed Consent – Self Motion Illusions in VR

Primary Investigator: Daniel Feuereissen, SFU-SIAT; email: dfeuerei@sfu.ca, ORE# 39101

Thank you
for participating in this study. Your contribution will help us better understand human behavior in real and mediated environments such as theme park rides, computer games or training simulators.

Compensation and Duration
This study will take about 40-75 minutes and you will receive $15 in exchange for your participation. In case you are not eligible to participate in this study, you will receive $5 for your efforts.

Your Rights
If you have concerns, feel uncomfortable or do not want to further engage in this study, please notify the study supervisor. You have the right to withdraw from this study at any time for full payment. No explanations are necessary. This university and those conducting this research do so based on ethical principles to protect your interests, safety and comfort. If you have concerns about your health, safety, psychological wellbeing or rights as a participant, or have a complaint about your treatment during this study, please contact the Director of the Office of Research Ethics per email (hal_weinberg@sfu.ca) or telephone (778-782-6593). It is your right to obtain research results found in this study and you may ask the experimenter to get back to you.

Confidentiality
Any information collected in this study will be kept confidential and safe to the extent permitted by law. That is, we will not associate your personal information with any data collected during the experiment. When we record your personal information we do so for administrative purposes only. We keep the study data on password protected storage devices and the paper forms in locked cabinets in an access restricted room for at least 2 years.

Risks to you
This study is non-invasive and will not harm or expose you to any undue danger. However, some individuals experience motion sickness while using our setup. If you have a history of motion sickness, please inform the experimenter. If you uncomfortable at any time during the experiment please alert the experimenter!

Your consent
I acknowledge that I have received, read and fully understood this document and the experiment Instruction document. I confirm that I am at least 19 years of age and voluntarily participate in this study. I know my rights, risks, and confidentiality involved in this study. Feel free to take a copy of all forms with you.

_____|_____
_____Date, Your Name (Last, First), Email or Telephone Number, Signature | Witness Signature

Instructions

Instructions – Self-Motion Illusions in Virtual Reality

Primary Investigator: Daniel Feuereissen, SFU-SIAT; email: dfeuerei@sfu.ca

Dear participant,
Welcome to the iSpace Lab and thank you for your participation in this Virtual Reality Study!

Now, please turn off all cell phones, pagers, etc. for the duration of the experiment.

Procedure and tasks:

This experiment will take about 60 minutes and consists of a screening phase, a learning phase, experiment trials and a short debriefing phase. You will be rewarded $15.

Perception of Self-Motion Illusions Screening Phase
Not everybody does perceive self-motion illusions on our type of setup. However, the ability to perceive self-motion illusions is key for this study. Therefore, you will undergo a short screening phase. The screening phase will help you to gauge the intensity of perceived self-motion later on in the experiment. The most intense sensation of motion that you will experience during the screening session is defined as 100% and no self-motion perception at all is defined as 0%. When you judge self-motion intensity later on during the experiment, please use your self-motion experiences from the screening phase as a basis and be consistent.

Main Experiment Phase
A) You will move within a 3D world on various paths by one of the following means: Joystick, chair, being pushed or just passively watching the scene. Make sure to follow the follow-me object (green cube) closely and focus your eyes on it!
Important: Relax during all viewing conditions of this experiment.

B) As soon as you experience any sensation of self-motion, notify the experimenter by saying a short word (e.g. “now!”) so that he can take note of it. You only need to do this once per path and it is important that you do this reliably during the entire study.

C) At the end of each path, verbally report the perceived intensity of self-motion (based on your experiences from the screening phase).

Questions in between trials:
After each trial, you will see two consecutive questions asking you about your experience during the previous trial. Each question is answered by moving a slider up or down on the screen using the joystick. Hold it in the desired position and then press any joystick-button to confirm.

Debriefing Phase after experiment

Please ask if anything is unclear or you have any questions.

Again, thank you for your participation, Daniel

Appendix B: ORE approval

SFU SIMON FRASER UNIVERSITY
THINKING OF THE WORLD

H. Weinberg, Ph.D.
Director, Office of Research Ethics
Simon Fraser University

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Multi-Tenant Facility
Burnaby, B.C. Canada , V4A 1S6
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Minimal Risk Expedited Approval

Date	File	Approval	Principal Investigator
8 Nov. 2011	[2010s0772]	Approved	Feuereissen, Daniel

Title	Start Date	End Date
Spatial perception and behavior in real and mediated environments	8 Nov. 2011	8 Nov. 2014

SFU Position	Department / School	Supervisor
Graduate Student	SIAT	Riecke, Bernhard

Hello Daniel,

Your application has been categorized as 'Minimal Risk' and approved by the Director, Office of Research Ethics on behalf of the Research Ethics Board, in accordance with University Policy r20.01 (http://www.sfu.ca/policies/research/r20.01.htm)

The Research Ethics Board reviews and may amend decisions made independently by the Director, Chair or Deputy Chair at the regular monthly meeting of the Board.

Please acknowledge receipt of this Notification of Status by email to dore@sfu.ca and Include the file number as shown above as the first item in the Subject Line.

You should get a letter shortly. Note: All letters are sent to the PI addressed to the Department, School or Faculty for Faculty and Graduate Students. Letters to Undergraduate Students are sent to their Faculty Supervisor.

Good luck with the project,

Hal Weinberg, Director