To Move or Not to Move: Can Active Control and User-Driven Motion Cueing Enhance Self-Motion Perception ("Vection") in Virtual Reality?

Bernhard E. Riecke*
Simon Fraser University, Canada

Daniel Feuereissen†
Simon Fraser University, Canada

Abstract

Can self-motion perception in virtual reality (VR) be enhanced by providing affordable, user-powered minimal motion cueing? To investigate this, we compared the effect of different interaction and motion paradigms on onset latency and intensity of self-motion illusions ("vection") induced by curvilinear locomotion in projection-based VR. Participants either passively observed the simulation or had to actively follow pre-defined trajectories of different curvature in a simple virtual scene. Visual-only locomotion (either passive or with joystick control) was compared to locomotion controlled by a modified Gyroxus gaming chair, where leaning forwards and sideways (±10cm) controlled simulated translations and rotations, respectively, using a velocity control paradigm similar to a joystick. In the active visual+chair motion condition, participants controlled the chair motion and resulting virtual locomotion themselves, without the need for external actuation. In the passive visual+chair motion condition, the experimenter did this. Self-motion intensity was increased in the visual+chair motion conditions as compared visual-only motion, corroborating the benefit of simple motion cueing. Surprisingly, however, active control reduced the occurrence of vection and increased vection onset latencies, especially in the chair motion condition. This might be related to the reduced intuitiveness and controllability observed for the active chair motion as compared to the joystick condition. Together, findings suggest that simple user-initiated motion cueing can in principle provide an affordable means of increasing self-motion simulation fidelity in VR. However, usability and controllability issues of the gaming chair used might have counteracted the benefit of such motion cueing, and suggests ways to improve the interaction paradigm.

CR Categories: H.1.2 [Models and Principles]: User/Machine Systems—Human factors, Human information processing H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities H.5.2 [Information Interfaces and Presentation]: User Interfaces—Input devices and strategies, Interaction styles J.4 [Social and Behavioral Sciences]: Psychology

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

1 Introduction

When moving about our environment, we naturally perceive and believe that we are indeed moving. While this seems trivial in natural environments, it cannot be taken from granted for mediated environments like virtual environments, computer games, or movies. In fact, we hardly perceive compelling, embodied self-motion in such mediated environments at all unless the displays occupy a large portion of our visual field of view (FOV) such as in IMAX cinemas, and/or actual, physical locomotion is provided (e.g., through motion platforms or free-space walking areas). While the technology for such large-FOV displays and physical locomotion interfaces is becoming increasingly sophisticated and powerful, it remains rather expensive and requires a considerable amount of space, effort, technological expertise and long-term support, thus preventing widespread adoption.

Could we reduce the requirement for large-screen displays and physical locomotion devices by focusing our efforts not on *physically correct* sensory stimulation, but instead on *perceptually effective* simulation? More than a century ago, researchers described how large-field visual motion (e.g., staring at a large waterfall from close by) can induce a compelling embodied illusion of self-motion, despite the lack of any physical locomotion [Mach 1875; Fischer and Kornmüller 1930; Tschermak 1931]. Many readers might have experienced such illusory self-motion ("vection") in the so-called train illusion: When sitting in a train waiting to depart from the station and seeing the train on the adjacent track pulling out of the station, one can get the compelling (albeit erroneous) sensation that one's own train is moving, not the adjacent one.

Similar, but typically weaker self-motion illusions can be obtained in blindfolded observers when stepping along a rotating floor on a carousel-like circular treadmill [Bles 1981] or listening to moving sound fields [Dodge 1923; Hennebert 1960; Lackner 1977; Marme-Karelse and Bles 1977]; or recent reviews see [Riecke et al. 2009b; Väljamäe 2009]. These early observations have inspired a long tradition of investigating how different factors contribute to these embodied and thus highly compelling illusions. Comprehensive reviews on visually-induced vection in general are provided by [Andersen 1986; Dichgans and Brandt 1978; Howard 1982; Howard 1986; Mergner and Becker 1990; Warren and Wertheim 1990]. More recently, self-motion illusions have been proposed as a lean-and-elegant means of providing compelling self-motion sensations in computer-simulated environments such as Virtual Reality (VR) [Riecke et al. 2005], and are reviewed in [Hettinger 2002; Riecke 2010; Väljamäe 2009].

One challenge for using self-motion illusions in applications such as motion simulation is that the illusion typically does not start immediately with the onset of the moving stimulus, but only gradually builds up after a so-called vection onset latency, which can range from a few seconds to half a minute. A major applied goal of vection research is thus to reduce the vection onset latency, as well as increase the overall intensity of perceived self-motion.

Besides this applied potential, vection research always includes a basic research component, as it can foster our understanding and theoretical models about multi-modal sensory integration [Mergner and Becker 1990; Wertheim 1994; Becker et al. 2002]: Whenever illusory self-motion is perceived, this indicates that those cues indicating self-motion (e.g., moving visual or auditory stimuli) start to dominate over competing cues that indicate stationarity, most predominately vestibular and other proprioceptive cues.

---

*e-mail: ber1[at]sfu.ca
†e-mail: feuereissen[at]gmail.com

The definite version was published as: Riecke, B. E., & Feuereissen, D. (2012). To Move or Not to Move: Can Active Control and User-Driven Motion Cueing Enhance Self-Motion Perception ("Vection") in Virtual Reality? ACM Symposium on Applied Perception SAP (pp. 17–24). Los Angeles, USA: ACM.

A variety of factors have been found to systematically affect self-motion illusions, as reviewed in detail in [Andersen 1986; Dichgans and Brandt 1978; Hettinger 2002; Howard 1982; Mergner and Becker 1990; Riecke 2010; Warren and Wertheim 1990]. Here, we focus on investigating three factors that have received relatively little attention in prior research, but could turn out to be relevant both from an applied and theoretical perspective.

1.1 How does Rotational Velocity Affect Curvilinear Vection?

Using a large-FOV panoramic Virtual Reality display and a variety of different motion directions and trajectories, Trutoiu at al. demonstrated that linear forward vection was less compelling than circular vection, whereas curvilinear vection (i.e., vection induced by driving along a curved path) was as compelling as circular vection [Trutoiu et al. 2009]. The authors concluded that "if vection is important to a VE application then curvilinear paths, instead of only linear paths, should be used when possible" [p. 56]. The authors did not, however, investigate how the degree of path curvature (or rotational velocity) might affect vection. The few studies that directly addressed this showed inconsistent findings: Whereas curvilinear vection induced by moving sine wave gratings in [Sauvan and Bonnet 1993] did not vary systematically with rotational velocity, a more recent study that used a naturalistic environment in immersive, projection-based VR reported enhanced vection for increasing rotational velocities [Riecke 2006]: Vection intensity increased, and vection onset latency was marginally reduced. The current study was designed to investigate if the proposed vection-enhancing effect of increasing rotational velocity in VR can be confirmed if a simple optic flow-based virtual environment is used instead of a naturalistic scenery. To this end, we compared curvilinear paths of 8°/s or 24°/s rotational velocity.

1.2 Can Minimal User-Initiated Motion Cueing Facilitate Vection?

Although motion cueing is frequently used in industry applications such as driving or flight simulation to improve the realism of motion simulation, there is surprisingly little published research on how such motion cueing affects or might trigger self-motion illusions. Wong and Frost demonstrated that circular vection induced by a rotating optokinetic drum occurs earlier if the onset of the visual motion is accompanied by concomitant physical observer rotation (1.1sec motion of 30° deflection with maximum acceleration of $240°/s^2$) [Wong and Frost 1981]. Although this vection-facilitating effect of consistent multi-modal stimulation is often attributed to a reduction in the inter-sensory cue conflict [Seno et al. 2011; Wong and Frost 1981], recent studies comparing head motions that were either consistent or inconsistent with display motions suggest that increasing inter-sensory conflict does not always have to impair vection [Ash et al. 2011; Palmisano et al. 2011].

A vection facilitation similar to [Wong and Frost 1981] was observed for linear forward vection induced in naturalistic VR if the visual motion onset was accompanied by a small physical motion (a small push of 1cm at $0.8m/s^2$ or 3cm at $1.6m/s^2$) controlled by a Stewart motion platform, resulting in reduced vection onset latencies and increased intensity and convincingness of vection [Riecke et al. 2006; Schulte-Pelkum 2007, exp. 5]. Similar facilitation of vection (although with somewhat reduced effect size) was observed if participants were seated on a wheelchair in front of a projection screen and small forward motions of about 1cm amplitude were manually applied by the experimenter holding the wheelchair [Schulte-Pelkum 2007, exp. 6]. Finally, and most closely related to the current study, Riecke demonstrated significant vection facilitation in all dependent measures if participants applied such motion cueing *themselves* on a modified manual wheelchair, without the need for any motors or an experimenter to move participants [Riecke 2006]: In their study, participants were seated on a manual wheelchair that was equipped with elastic bands that prevented the wheels from turning more than about 10°. This provided a simple force-feedback velocity control paradigm similar to a joystick, in that small translational and rotational wheelchair motions (restricted to 8cm and 10°, respectively, by the elastic rubber bands) resulted in visually simulated motion velocities proportional to the wheelchair displacement from the default position.

Figure 1: *Gyroxus gaming chair.*

The current study aimed to test if a similar benefit of user-powered motion cueing can be observed when using an off-the-shelf Gyroxus gaming chair (see Figure 1), where simulated translations and rotations are controlled by the user leaning forwards and sideways with the chair, respectively, as if the chair was one large joystick (see `iSpaceLab.com/project/Gyroxus` for illustrations). To the best of our knowledge, this is the first study to test if the motion control paradigm offered but such commercially available gaming chairs can in fact enhance the users' sensation of self-motion.

1.3 Interactivity: How is Vection Affected by Passive Viewing vs. Active Control?

Despite the overall large number of vection studies, there are few (if any) studies that directly address the potential effect of passive viewing vs. active control of locomotion on vection. In fact, most vection studies seem to have used passive stimulus presentation, in the sense that participants had no direct control over the velocity or direction of the moving visual or auditory stimulus or the simulated self-motion trajectory. In many real-world and VR situations, however, humans actively control the direction and velocity of self-motion. Hence, we designed the current study to address how passive viewing versus active control of locomotion might affect visually-induced vection. To this end, we compared active control of locomotion (using a joystick or Gyroxus motion chair) to passively observing the locomotion.

Although there seem to be no studies that directly investigated the potential influence of passive versus active control of locomotion on vection, there are studies from related fields showing various benefits of active control. For example, optic flow-based self-motion perception can be fairly accurate even during active head turning, an effect that is mediated by a combination of three extra-retinal cues: neck proprioception, vestibular stimulation, and efference copy of the active head turning [Crowell et al. 1998]. Similarly, active observers incorporate such extra-retinal signals, yielding to the finding that active and passive observers perceive 3-dimensional spatial structure and the stationarity of objects therein differently, even when a visual stimulus is identical [Wexler et al. 2001]. Actively controlling one's locomotion can also reduce motion sickness, not only for physically moving vehicles like cars or rotation platforms [Rolnick and Lubow 1991], but also for only visually simulated motion [Dong et al. 2011], which might be relevant for VR applications where users are often prone to simulator sickness. Finally, spatial cognition and spatial learning often benefits from active control of locomotion [Chrastil and Warren 2012]. Contributing factors include the act of actively allocating attentional resources to relevant features of the environment and the availability idiothetic cues [Mittelstaedt and Mittelstaedt 2001], which include both efferent motor commands and re-afferent vestibular and proprioceptive self-motion information.

While caution is needed when extrapolating from these findings, we expected that active control of locomotion and the resulting attentional demands might enhance vection in the current study. This prediction is also based on findings that the onset latency of forward linear vection in VR can be reduced by performing an attention-demanding working-memory task (counting specific targets moving by in the visual stimulus)[Trutoiu et al. 2008]. Attention has also been shown to modulate the occurrence and direction of vection when two superimposed vection stimuli are presented [Kitazaki and Sato 2003].

2 Methods

Sixteen participants (7 female) aged 18-45 years (mean: 25.9) completed the experiment for standard payment. All participants had normal or corrected-to-normal vision and no signs of vestibular dysfunction as assessed through a Romberg test [Khasnis and Gokula 2003]. Four additional participants were excluded in a pre-test as they did not report vection in the vection demonstration phase.

2.1 Stimuli and Apparatus

2.1.1 Visualization

Throughout the experiment, participants wore passive polarizing glasses and were seated on a Gyroxus motion chair 1.30m from a flat polarisation-preserving screen of 2.45m × 1.55m as illustrated in Figure 2. Visual stimuli were projected stereoscopically using two InFocus IN5504 projectors of 1920 × 1200 pixel resolution each equipped with polarization filters. Together with the surrounding black fabric tent, this resulted in an immersive stereoscopic view subtending a visual field of view of 74° × 52° for the observers seated upright.

2.1.2 Dynamic Viewpoint Tracking

To emphasize the metaphor of the projection screen being a window onto the virtual world, the viewing frustum was dynamically adjusted depending on participants' head position with respect to the projection screen. That is, when participants changed head position, the view onto the simulated scene changed as if looking through a window defined by the screen boundaries. For example, when participants moved their head a bit closer to the screen, the simulated FOV increased to match the increased physical FOV under which the screen boundaries were seen. Head tracking was achieved via a 6DoF Polhemus Liberty magnetic tracker attached to the participants' headphones.

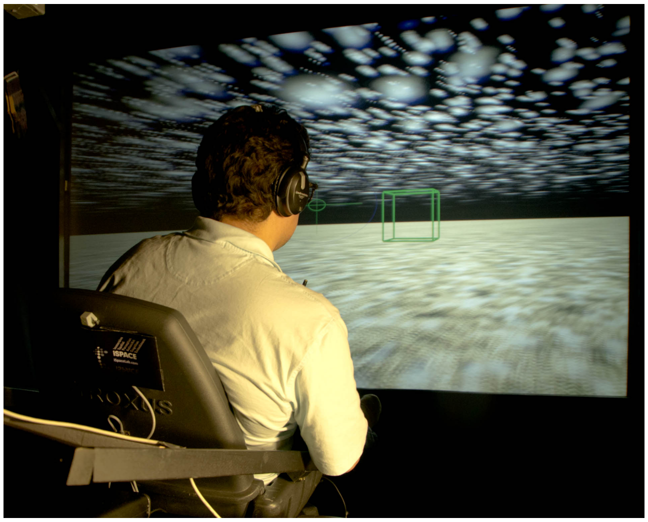

Figure 2: *Experimental setup, showing a participant on the Gyroxus motion chair seated behind the stereo projection screen. The virtual scenery consisted of a simple textured ground plane and randomly positioned stationary white blobs above and below the participants' viewpoint. During active trials, participants were asked to use the given interaction paradigm (joystick or Gyroxus motion chair) to closely follow the green follow-me cube such that it stayed within the central screen area defined by the crosshair and blue circle (see* `iSpaceLab.com/project/Gyroxus` *for illustrations).*

2.1.3 Virtual Scenery

As illustrated in Figure 2, the simulated scene consisted of a simple textured ground plane and several layers of randomly positioned white blobs both above and below the participants' viewpoint, somewhat resembling large snowflakes. These white blows were faded out at far distances to avoid rendering artifacts. The scene was designed to provide strong optic flow and parallax information to facilitate vection, but no landmarks.

2.1.4 Sound

To exclude potentially interfering ambient sound from the lab, participants wore active noise-canceling headphones (Audiotechnica ATH-ANC7) that displayed a mixed-river masking sound at moderate volume. In addition, the headphones were used for providing computer-generated verbal instructions.

2.1.5 Interaction and Motion Paradigms

As detailed above, this study was designed to investigate how visually-induced self-motion illusions might be affected by the interaction and motion paradigm used. To this end, we used a fully crossed 2 × 2 design to investigate the relative contribution of two parameters that have received little attention in prior research: (1) simple motion cueing (using a Gyroxus gaming chair), and (2) active control of the simulated self-motion (see Table 1).

In the **visual-only motion** condition, the participants' chair was held stationary, and the simulated self-motion was either controlled by participants using a joystick mounted in front of them **(active condition**) or software-controlled (**passive condition**). In the **visual+chair motion** condition, the Gyroxus motion chair that participants were sitting on was used to control the visually simulated

	passive (participants have no control over simulated self-motion)	**active** (participants control simulated self-motion)
visual only motion	stationary "watch" condition	Joystick-controlled motion
visual+chair motion	Experimenter controls chair	Chair-controlled motion

Table 1: *Different motion and interaction paradigms used.*

self-motion: In the **active condition**, participants leaned with the chair into the direction of intended travel, as if the chair was one huge joystick (see `iSpaceLab.com/project/Gyroxus` for illustrations). That is, by using the handle bar and shifting ones weight through leaning, participants could deflect the chair from its default middle position by about ± 10cm in the front-back and left-right direction. Chair deflections from the default centered position were measured using a Polhemus Liberty position tracker and were used to control the visually simulated motion, with motion parameters matching the joystick controls: Forward/backward deflection of the joystick or chair controlled the forward/backward translational velocity, whereas sideways (left/right) deflection controlled the rotational velocity. In the **passive visual+chair condition**, the chair motion was controlled by the experimenter who was trained to produce similar motion profiles as participants. Similarity between experimenter- and participant-produced motion profiles was confirmed by recording and analyzing the respective velocity profiles for all trials. Note that the experimenter did not have advance knowledge of the upcoming rotational velocity or turning direction, just like participants in the active condition.

2.1.6 Trajectories

To achieve similar motion trajectories and velocity profiles in all four motion conditions, participants in the active motion conditions were asked to closely follow a green follow-me cube that moved along pre-defined trajectories (see Fig. 2). In the passive motion conditions, the same follow-me object was presented, but simulated self-motion was controlled either by the computer (for the visual-only passive motion condition) or by the experimenter (for the visual+chair passive motion condition). To ensure similar viewing conditions, participants were asked to always look at the green cube in a relaxed manner.

The follow-me object travelled at 5m/s on one of four different pre-defined trajectories of 32s duration. These trajectories consisted of a 6m initial straight segment, followed by a smooth turn of 126m length in either left or right direction, and a final 10m straight segment. Turn velocities were either 8°/s or 24°/s, with an initial acceleration and final deceleration phase of $8°/s^2$ and $24°/s^2$, respectively, yielding total turning angles of 192° and 576°, respectively. To reduce the occurrence of simulator sickness, motions started and ended with smooth linear accelerations and decelerations of $1m/s^2$. Maximum joystick and chair deflection resulted in velocities about twice as large as the maximum velocity of the follow-me object, such that participants could easily catch up if needed.

2.2 Procedure and Experimental Design

After signing informed consent and receiving written and oral instructions, participants were seated on the Gyroxus chair and exposed to two passive visual+chair-motion demo trials of 82s length that included a 24°/s rotation of 1728°. During these demo trials, the experimenter explained the follow-me task, the concept of vection, and how participants were to verbally indicate the onset of vection during the subsequent experiment. At total of four participants were excluded as they did not perceive vection during this vection demonstration phase. In two subsequent active visual+chair-motion trials of 32s duration, participants controlled the motions themselves and the experimenter provided guidance where needed.

Once participants were familiar with the experimental requirements, they performed 8 vection trials in a fully crossed within-participant design. This consisted of a factorial combination of 2 turning velocities (8°/s vs. 24°/s, alternating every trial) × 2 physical motion conditions (visual only motion vs. visual+chair motion, alternating every two trials) × 2 interactivity conditions (passive vs. active, switching after four trials). Turning direction (left/right) was randomized per trial, while the order of the other conditions was balanced across participants. Before each of the active motion conditions, participants were given time to familiarize themselves with the joystick/chair motion paradigm and practiced until they could easily follow the follow-me object which moved in alternating turns of randomized radii. The whole experiment took 1/2 hour on average, after which participants were debriefed and thanked for their participation.

2.3 Dependent Variables

For each trial, participants were asked to verbally report as soon as they started experiencing any vection. This defined the **vection onset latency**. As vection was not perceived by all participants in all trials, the following procedure was used to avoid discarding those trials and thus biasing the results [Riecke et al. 2009a]: Whenever no vection was perceived, vection onset latency was assigned to the maximum trial duration, which was 32s. Note that this is a conservative estimate of the vection onset latency in the following sense: If participants would have perceived vection for longer trials (as is not unlikely), the resulting vection onset latencies would all be beyond 32s. Hence, any statistical result should hold true if we would have used a longer stimulus presentations and participants might eventually have perceived vection. The **percentage of trials where participants reported any vection** was used as an additional corroborative measure of the vection-inducing potential of the different experimental conditions. After each trial, participants verbally rated the **intensity of vection** on a scale from 0-100%.

3 Results and Discussion

Vection data are summarized in Figure 3 and were analyzed using separate repeated measures ANOVAs for the three dependent measures vection intensity, vection onset latency, and percentage of trials with vection (see Table 2). Independent variables for in the ANOVAs were the within-participant factors turning velocity, motion condition, and interactivity. Greenhouse-Geisser correction was applied where needed.

3.1 Turning Velocity (8°/s vs. 24°/s)

Turning velocity showed a significant main effect on vection intensity (see Table 2), with larger velocities yielding higher vection intensity ratings (63.7% vs. 50.0%). Moreover, larger turning velocities produced marginally reduced vection onset latencies (11.0s vs. 14.3s) and marginally more trials where vection was experienced (93.8% vs. 81.3%).

This overall enhancement of vection for larger rotational velocities on curvilinear paths confirms earlier findings [Riecke et al. 2006] and extends them to optic flow-based virtual environments like the one used in the current study. It is unclear, however, how vection might be affected by larger turning velocities than the maxi-

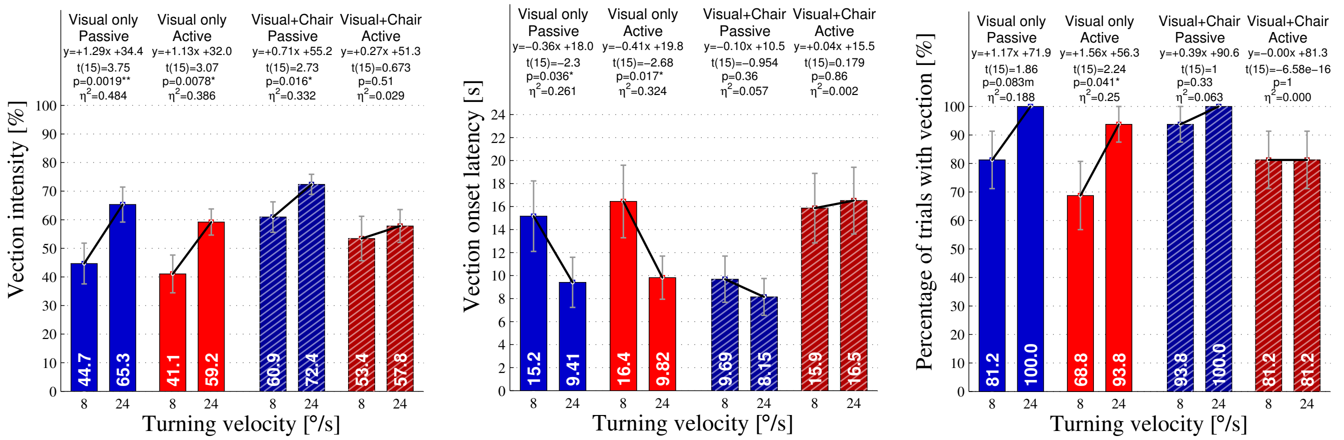

Figure 3: *Arithmetic means ± 1SEM for the different conditions and dependent measures. t-tests of the linear regression slopes were used to test for significant increase/decrease of the dependent measures with increasing turning angle.*

	Vection intensity			Vection onset latency			Percentage of no-vection trials		
	F(1,15)	p	η_p^2	F(1,15)	p	η_p^2	F(1,15)	p	η_p^2
Turning velocity {8°/s, 24°/s}	**13.77**	**.002****	**.479**	*4.44*	*.052m*	*.228*	*3.75*	*.072m*	*.200*
Motion condition {visual only, visual + chair motion}	**5.00**	**.041***	**.250**	.016	.902	.001	.319	.580	.021
Interactivity {passive, active}	2.00	.178	.118	**11.43**	**.004****	**.432**	**5.00**	**.041***	**.250**
Turning velocity × motion condition	**7.91**	**.013***	**.345**	**6.44**	**.023***	**.300**	*3.46*	*.083m*	*.188*
Turning velocity × interactivity	.569	.462	.037	.093	.764	.006	0.00	1.00	.000
Motion condition× interactivity	.578	.459	.037	**5.33**	**.036***	**.262**	.238	.633	.016
Turning velocity × motion condition × interactivity	.371	.552	.024	.274	.608	.018	.484	.497	.031

Table 2: *ANOVA results. Significant effects are typeset as bold, marginally significant effect in italics;* * *p<.05,* ** *p<.01,* *** *p<.001. The effect strengths partial* η_p^2 *indicates the percentage of variance explained by a given factor.*

mum of 24°/s used here. Pilot studies indicated that participants had increasing difficulties in controlling the simulation and staying closely behind the follow-me object for turning velocities exceeding 24°/s.

The facilitation of curvilinear vection for larger angular velocities observed here also corroborates and extends findings from circular vection studies using optokinetic drums, where vection is generally enhanced for increasing stimulus velocities [Allison et al. 1999; Brandt et al. 1973; Dichgans and Brandt 1978; Howard 1986], at least up to a certain optimal velocity of around 120°/s for optokinetic drums [Brandt et al. 1973]. Further studies are needed to determine if there might be a similar optimal velocity where vection peaks for curvilinear motion. If so, this might be relevant for many applications including driving or flight simulations, where curvilinear motions are frequent. It is likely that the optimal vection-inducing rotational velocity in VR will be much lower than the 120°/s reported for optokinetic drums, though, as visual artifacts in VR simulations become increasingly noticeable for rotational velocities exceeding 60°/s, mostly due to the limited update rate of the displays (typically 60Hz currently).

3.2 Motion Condition (Visual Only vs. Visual+Chair Motion)

Adding chair motion to the visual motion significantly increased vection intensity ratings (from 52.7% to 61.1%), but showed no significant main effects on vection onset latency or the occurrence of vection. These main effects were qualified by significant or marginally significant interactions (see Table 2 and Figure 3), indicating that the vection-enhancing effect of the added chair motion was more pronounced for lower turning velocity and thus weaker vection-inducing visual stimuli. In part, this might be related to a ceiling effect, in that vection onset latencies were already rather low in the visual-only conditions for the faster turning velocities, whereas there was more room for improvement for the lower turning velocities.

While the overall vection-facilitating effect of the added minimal motion cueing confirms earlier research [Riecke 2006; Riecke et al. 2006; Schulte-Pelkum 2007; Wong and Frost 1981] and extends it to the leaning-motion used by the current gaming chair, the effect size was smaller than anticipated. For example, while adding small physical motions for curvilinear vection conditions in [Riecke et al. 2006] significantly increased vection intensity ratings by 43%, the current study only showed a moderate increase by 16%. In particular, the lack of an effect on vection onset latency was rather unexpected in the light of prior research: Whereas vection onset latencies in [Riecke et al. 2006] decreased by 31% (from 7.3s to 5.0s) when small physical motions where added, the current study showed no such benefit (12.7s vs. 12.6s).

A variety of factors could have contributed to this difference, including differences in the motion paradigms and the vection-inducing potential of the visual as well as physical motion cues. We are planning follow-up studies to directly compare the vection-facilitating effect of self-powered motion cueing of different motion paradigms including the wheelchair-based approach proposed by [Riecke 2006] and the ChairIO approach proposed by [Beckhaus et al. 2005].

3.3 Interactivity (Passive vs. Active)

Unexpectedly, switching from passively observing to active control of locomotion significantly impaired vection: Vection onset latencies were raised from 10.6s to 14.7s, and the occurrence of vection was reduced from 93.8% to 81.3%. There was a similar (but non-significant) decrease in vection intensity ratings from 60.8% to 52.9% when switching to active control.

Vection onset latencies showed a significant interaction between motion condition and interactivity: On the one hand, allowing participant to use the joystick to control simulated self-motions in the visual only conditions had little if any effect on vection (see Fig. 3). As participants were familiar with using a joystick to navigate, this suggests that adding interactivity might not by itself improve vection. On the other hand, switching from passive to actively controlled locomotion using the gyroxus motion chair almost doubled vection onset latencies. That is, whereas switching to joystick-controlled locomotion showed little effect on vection, switching to active Gyroxus-controlled locomotion impaired vection considerably.

Given the often observed benefit of active control over passive observation in various tasks (see subsection 1.3), the finding that active control of the motion chair decreased vection instead of increasing it came somewhat as a surprise. The differential effect of interactivity dependent on joystick- vs. Gyroxus-control suggests that the relevant parameter here was not interactivity per se but the specifics of motion control used in the active conditions. Post-experimental interviews suggest indeed that participants encountered difficulties in adapting to the interaction paradigm and somewhat jerky motions of the Gyroxus chair interface, but had no difficulties using the joystick. This is discussed in more detail below.

3.4 Controllability and Precision Offered by joystick vs. Gyroxus Motion Chair

To assess how well and precisely participants could use the different input methods to control their simulated locomotion, participants were asked in the debriefing to rate "how well could you navigate and follow the green cube with joystick vs. chair", on a scale from 0-100%. Ratings were significantly lower for the chair input method (t(15)=-5.15, p<.001***, η_p^2=.998, see also Figure 4). Together with post-experimental interview data, these findings suggest that the Gyroxus gaming chair interface is in fact not as easy and intuitive to use as expected and advertised. Despite a practice phase of several minutes, most participants still preferred the joystick input device, especially when precise and accurate control is needed.

3.5 Conclusions and Outlook

The current study provides three major novel findings. First, curvilinear vection was enhanced for more narrow turns (and thus higher rotational velocities). This corroborates earlier findings that were observed in a naturalistic city environment [Riecke et al. 2006] and extends them to simple optic flow-based VR.

Second, minimal motion cueing applied using an off-the-shelf Gyroxus gaming chair enhanced the intensity of vection. On the one hand, this corroborates the benefit of physical motion cueing observed in [Riecke et al. 2006] for a wheelchair-based motion model and extends it to the rather different motion paradigm of the Gyroxus gaming chair. On the other hand, the facilitation effect was less than expected based on [Riecke et al. 2006], suggesting that the type and specifics of the motion cueing play a major role.

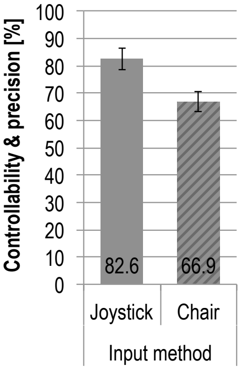

Figure 4: *Post-experimental rating of how well participants could "navigate and follow the green cube" with the the input method joystick vs. Gyroxus motion chair.*

Third, the current study was (to the best of our knowledge) the first to directly investigate how passive versus active control of locomotion might affect vection. On the one hand, switching from passive viewing to joystick-based active control did not show any clear effect on vection. On the other hand, switching from being passively moved on the Gyroxus gaming chair to having to actively control it decreased vection instead of facilitating it as predicted. This finding was indeed puzzling and awaits further investigation. There are several factors that might have contributed. For example, the need to actively control the locomotion with a gaming chair that participants were not very familiar with might have increased attentional demands and thus indirectly reduced participants' attention to the visual vection-inducing stimulus and/or changed their viewing and fixation patterns. Participants might also simply have been too preoccupied with controlling the Gyroxus chair (especially for more narrow turns) to pay sufficient attention to their self-motion experience and report it as reliably.

Whereas being passively moved in the Gyroxus gaming chair enhanced vection, having to actively control it impaired vection. Based on this finding, one might hypothesize that more extensive practice with the chair interface might help to reduce the costs of active control and provide at least some of the benefits of the physical chair motions. First follow-up tests suggest that the vection impairment observed for the active Gyroxus motion conditions might indeed be related to insufficient practice and experience in controlling the Gyroxus gaming chair. We are currently running follow-up studies do investigate this hypothesis further.

In conclusion, although the vection experience was more intense when adding chair motions to the visual simulation, the current data point to various shortcomings of the existing chair interface that would need to be improved before reaching its full potential, especially when active control is intended. That is, while user-powered motion cueing seems to be a promising concept worth exploring further, there are various design challenges that would need to be addressed. Psychophysical studies like the current vection paradigm might provide an experimental tool to guide and inspire such future research and development, thus bringing us closer to our long-term goal of designing and iteratively improving affordable yet effective self-motion simulation paradigms.

Acknowledgements

We would like to thank Markus von der Heyde for inspiring discussions and technical support and NSERC for funding.

References

ALLISON, R. S., HOWARD, I. P., AND 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*, 3, 299–306. PMID: 10615468.

ANDERSEN, G. J. 1986. Perception of Self-Motion - psychophysical and computational approaches. *Psychological Bulletin 99*, 1 (Jan.), 52–65.

ASH, A., PALMISANO, S., AND KIM, J. 2011. Vection in depth during consistent and inconsistent multisensory stimulation. *Perception 40*, 2, 155–174.

BECKER, W., NASIOS, G., RAAB, S., AND JÜRGENS, R. 2002. Fusion of vestibular and podokinesthetic information during self-turning towards instructed targets. *Experimental Brain Research 144*, 4 (June), 458–474.

BECKHAUS, S., BLOM, K. J., AND HARINGER, M. 2005. A new gaming device and interaction method for a First-Person-Shooter. *Proceedings of the Computer Science and Magic 2005*.

BLES, W. 1981. Stepping around: circular vection and coriolis effects. In *Attention and performance IX*, J. Long and A. Baddeley, Eds. Erlbaum, Hillsdale, NJ, 47–61.

BRANDT, T., DICHGANS, J., AND KOENIG, E. 1973. Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research 16*, 476–491.

CHRASTIL, E. R., AND WARREN, W. H. 2012. Active and passive contributions to spatial learning. *Psychonomic Bulletin & Review 19*, 1 (Feb.), 1–23.

CROWELL, J. A., BANKS, M. S., SHENOY, K. V., AND ANDERSEN, R. A. 1998. Visual self-motion perception during head turns. *Nature Neuroscience 1*, 8 (Dec.), 732–737.

DICHGANS, J., AND BRANDT, T. 1978. Visual-Vestibular interaction: Effects on Self-Motion perception and postural control. In *Perception*, vol. VIII of *Handbook of Sensory Physiology*. Springer, 756 – 804.

DODGE, R. 1923. Thresholds of rotation. *Journal of Experimental Psychology 6*, 2, 107–137.

DONG, X., YOSHIDA, K., AND STOFFREGEN, T. A. 2011. Control of a virtual vehicle influences postural activity and motion sickness. *Journal of Experimental Psychology: Applied 17*, 2 (June), 128–138.

FISCHER, M. H., AND KORNMÜLLER, A. E. 1930. Optokinetisch ausgelöste bewegungswahrnehmung und optokinetischer nystagmus [Optokinetically induced motion perception and optokinetic nystagmus]. *Journal für Psychologie und Neurologie*, 273–308.

HENNEBERT, P. E. 1960. Audiokinetic nystagmus. *Journal of Auditory Research 1*, 1, 84–87.

HETTINGER, L. J. 2002. Illusory self-motion in virtual environments. In *Handbook of Virtual Environments*, K. M. Stanney, Ed. Lawrence Erlbaum, 471–492.

HOWARD, I. P. 1982. *Human visual orientation*. J. Wiley, Chichester, New York, Engl.

HOWARD, I. P. 1986. The perception of posture, self motion, and the visual vertical. In *Sensory processes and perception*, K. R. Boff, L. Kaufman, and J. P. Thomas, Eds., vol. 1 of *Handbook of human perception and performance*. Wiley, New York, 18.1–18.62.

KHASNIS, A., AND GOKULA, R. M. 2003. Romberg's test. *Journal of Postgraduate Medicine 49*, 2, 169–172.

KITAZAKI, M., AND SATO, T. 2003. Attentional modulation of self-motion perception. *Perception 32*, 4, 475–484.

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.

MACH, E. 1875. *Grundlinien der Lehre von der Bewegungsempfindung*. Engelmann, Leipzig, Germany.

MARME-KARELSE, A. M., AND BLES, W. 1977. Circular vection and human posture, II. does the auditory system play a role? *Agressologie 18*, 6, 329–333.

MERGNER, T., AND BECKER, W. 1990. Perception of horizontal self-rotation: Multisensory and cognitive aspects. In *Perception & Control of Self-Motion*, R. Warren and A. H. Wertheim, Eds. Erlbaum, New Jersey, London, 219–263.

MITTELSTAEDT, M., AND MITTELSTAEDT, H. 2001. Idiothetic navigation in humans: estimation of path length. *Experimental Brain Research 139*, 3, 318–332.

PALMISANO, S., ALLISON, R. S., KIM, J., AND BONATO, F. 2011. Simulated viewpoint jitter shakes sensory conflict accounts of vection. *Seeing and Perceiving 24*, 2, 173–200.

RIECKE, B. E., SCHULTE-PELKUM, J., CANIARD, F., AND BÜLTHOFF, H. H. 2005. Towards lean and elegant Self-Motion simulation in virtual reality. In *Proceedings of IEEE Virtual Reality 2005*, 131–138.

RIECKE, B. E., SCHULTE-PELKUM, J., AND CANIARD, F. 2006. Visually induced linear vection is enhanced by small physical accelerations. In *7th International Multisensory Research Forum (IMRF)*.

RIECKE, B. E., FEUEREISSEN, D., AND 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. ACM ID: 1577763.

RIECKE, B. E., VÄLJAMÄE, A., AND SCHULTE-PELKUM, J. 2009. Moving sounds enhance the visually-induced self-motion illusion (circular vection) in virtual reality. *ACM Transactions on Applied Perception (TAP) 6* (Mar.), 7:1–7:27. ACM ID: 1498701.

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 (VRST)*, ACM, Limassol, Cyprus, 104–107.

RIECKE, B. E. 2010. Compelling Self-Motion through virtual environments without actual Self-Motion – using Self-Motion illusions ("Vection") to improve user experience in VR. In *Virtual Reality*. InTech, 161 – 188. Jae-Jin Kim (Ed.).

ROLNICK, A., AND LUBOW, R. E. 1991. Why is the driver rarely motion sick? the role of controllability in motion sickness. *Ergonomics 34*, 7 (July), 867–879.

SAUVAN, X., AND BONNET, C. 1993. Properties of curvilinear vection. *Attention, Perception, & Psychophysics 53*, 4, 429–435.

SCHULTE-PELKUM, J. 2007. *Perception of self-motion: Vection experiments in multi-sensory Virtual Environments*. PhD thesis, Ruhr-Universität Bochum.

SENO, T., ITO, H., AND SUNAGA, S. 2011. Inconsistent locomotion inhibits vection. *Perception 40*, 6, 747.

TRUTOIU, L. C., STREUBER, S., MOHLER, B. J., SCHULTE-PELKUM, J., AND BÜLTHOFF, H. H. 2008. Tricking people into feeling like they are moving when they are not paying attention. In *Applied Perception in Graphics and Visualization (APGV)*, 190.

TRUTOIU, L. C., MOHLER, B. J., SCHULTE-PELKUM, J., AND BÜLTHOFF, H. H. 2009. Circular, linear, and curvilinear vection in a large-screen virtual environment with floor projection. *Computers & Graphics 33*, 1 (Feb.), 47–58.

TSCHERMAK, A. 1931. Optischer raumsinn. In *Handbuch der Normalen und Pathologischen Physiologie*, A. Bethe, G. Bergmann, G. Embden, and A. Ellinger, Eds. Springer, 834–1000.

VÄLJAMÄE, A. 2009. Auditorily-induced illusory self-motion: A review. *Brain Research Reviews 61*, 2 (Oct.), 240–255.

WARREN, R., AND WERTHEIM, A. H., Eds. 1990. *Perception & Control of Self-Motion*. Erlbaum, New Jersey, London.

WERTHEIM, A. H. 1994. Motion perception during self-motion - the direct versus inferential controversy revisited. *Behavioral and Brain Sciences 17*, 2 (June), 293–311.

WEXLER, M., PANERAI, F., LAMOURET, I., AND DROULEZ, J. 2001. Self-motion and the perception of stationary objects. *Nature 409*, 6816 (Jan.), 85–88.

WONG, S. C. P., AND 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.