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Compelling Self-Motion Through Virtual Environments without Actual Self-Motion – Using Self-Motion Illusions ("Vection") to Improve User Experience in VR

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1. Introduction

While modern computer graphics and virtual reality (VR) simulations can have stunning photorealism, they are often unable to provide a life-like and compelling sensation of moving through the simulated world. This is in stark contrast to our real-world experience, where locomotion through the environment is naturally accompanied by the embodied sensation of self-motion, even when we are not actively walking but using other transportation devices like bicycles, cars, or buses. This fundamental difference in which we perceive simulated versus actual motions might negatively impact the perceived realism, behavioural effectiveness, user acceptance, and commercial success of virtual reality technology and applications. In this chapter, I propose and discuss how investigating, utilizing, and optimizing self-motion illusions ("vection") might be a lean and elegant way to overcome such shortcomings and provide a truly "*moving experience*" in computer-mediated environments without the need to physically move, thus reducing overall cost and effort.

The aim of this chapter is to provide an overview of the state of the art in research on visually-induced self-motion illusions in real and virtual environments. Specific focus will be on a topic that is of particular interest in the context of VR but has not been thoroughly reviewed before: Namely how self-motion illusions are not only affected by physical stimulus parameters themselves via bottom-up perceptual processes (as discussed in section 3), but also by the way we look at, perceive, and interpret the stimulus, how it is integrated into the overall display setup, and whether or not actual motion might be possible (see section 4). Knowledge of these factors can not only deepen our understanding of the complex processes underlying self-motion perception, but might also be of particular interest for VR simulations and other immersive/multi-media applications like gaming or movies, as these factors can often be manipulated with relatively little effort. Section 5 will provide a brief overview on recent studies on multi-modal contributions and interactions for vection. These indicate significant cross-modal benefits, which could, together with the results presented in earlier sections, be employed to design more effective-yet-affordable VR interfaces, as will be discussed in the final section and throughout this chapter. Possible side-effects of vection in VR are discussed in section 6.

2. Self-motion illusions ("vection")

Self-motion illusions induced by moving visual stimuli that cover a large part of the visual field have been first described more than a century ago (Mach, 1875; Wood, 1895), and were termed circular and linear vection for rotational and translational self-motion illusions, respectively (Fischer & Kornmüller, 1930; Tschermak, 1931). Many readers might have experienced the compellingness of visually-induced self-motion illusions themselves, as they can easily occur under natural conditions – for example, when sitting in a train waiting to depart from the station and looking out of the window where a train on the adjacent track starts moving, many people experience a rather convincing illusion that there own train started moving ("train illusion"). Similarly, when waiting in a car in front of a red light and a large truck slowly pulls up on the side, many of us instinctively hit the break as for a moment we believed that our own car was moving. One of the earliest occurrences of vection might have been when our ancestors were gazing at fast-moving clouds or looking down on a river and fixating onto a stationary object (like a rock) in the river and experienced a tilting sensation in the direction opposite of the visual (river) motion. More recently, large-screen theme park rides and cinemax or I-Max theatres utilize self-motion illusions to provide more compelling experiences to their audience, as was already done more than a century ago with the "haunted swing" illusion described by Wood (1895).

Why might we want to care about self-motion illusions in the context of VR and other immersive media? As mentioned above, most VR and immersive media setups and applications do not provide a compelling and believable sensation of moving through the simulated environments; despite often impressive visual realism, perceptual and behavioural realism is often lacking. That is, seeing a simulated self-motion does not necessarily imply experiencing and believing it, thus reducing overall believability and simulation quality. So what conditions are conducive to experiencing believable self-motion illusions?

There is more than a century of vection research investigating under what precise conditions moving visual and non-visual stimuli can induce embodied sensations of self-motion. I propose that revisiting, utilizing, and extending this body of knowledge can provide both inspiration and guidance for improving VR and other immersive media from the human/user perspective. In a nutshell, if we could provide users with a compelling illusion of moving through simulated worlds, we would not have to go through the effort of allowing for large-scale physical locomotion or could at least relax the requirement of those.

One of the biggest challenges in self-motion simulation is that some modalities simply cannot (yet) be simulated easily or switched off noninvasively: In particular, vestibular and most somatosensory cues cannot be simply "turned off" like visual cues (closing ones' eyes) or auditory cues (wearing earplugs and/or listening to masking noise). Hence, whenever self-motions are only simulated and not physically performed, there is a conflict between those cues suggesting self-motion (e.g., the visual simulation) and other cues indicating stationarity (e.g., vestibular cues indicating that there was no acceleration and we should thus still be stationary, or somatosensory cues from our feet touching solid ground). So how is this conflict and ambiguity resolved by the human system to form a coherent percept of one's current state of motion?

Indeed, self-motion perception is a complex phenomenon that includes multiple sensory and motor systems as well as both bottom-up processes and higher-level, cognitive influences, as will be discussed in the subsequent sections. There are several mathematical frameworks modelling how the different sensory and motor inputs might be integrated to form a coherent percept of self-motion despite conflicting or ambiguous information (e.g., Mergner & Becker, 1990; Mergner et al., 2000; Wertheim, 1994; Zacharias & Young, 1981). While vestibular motion cues immediately yield a sensation of self-motion, large-field visual motion can be interpreted as either object motion (where the observer is stationary) or self-motion (where the visual stimulus is stationary) or a combination thereof. When presented with coherent large-field visual motion, the observer typically perceives object motion during the first few seconds after motion onset (1-30s, depending on various stimulus parameters), followed by a sometimes very brief period of mixed object and self-motion, and finally exclusive self-motion and saturated vection (Dichgans & Brandt, 1978). During saturated vection, the moving stimulus is typically (but not always) perceived as earth-stationary, and vection occurs in the direction opposite of the visual motion (just as if we would be physically moving).

There is a long history of investigating how different stimulus parameters affect the onset, strength, and velocity of vection. General reviews on self-motion illusions can be found in (Andersen, 1986; Dichgans & Brandt, 1978; Howard, 1982, 1986; Mergner & Becker, 1990; Warren & Wertheim, 1990). Auditory vection has recently been reviewed by (Riecke et al., 2009; Väljamäe, 2009). Neurophysiological correlates of vection have been described in, e.g., (Hettinger, 2002; Kovacs et al., 2008) and references therein. Vection with a specific focus on motion simulation, virtual environments, and undesirable side-effects has been reviewed in (Hettinger, 2002).

The goal of the following section is to provide a current review on different stimulus parameters affecting visually-induced vection, and how these factors might be utilized in the design of VR and other immersive applications. Section 4 will focus on recent findings indicating that vection is not only affected by physical stimulus parameters themselves, but also by how we look at, perceive, and interpret the stimulus, by what is beyond the display itself, and by our sensation/knowledge whether actual motion might or might not be possible. The presented research findings lead to a number of possible applications and implications for VR and other immersive applications. Instead of summarizing them in a separate section, I decided to integrate them with the respective research findings to provide a stronger link and an improved understanding of their origin and underlying processes.

3. Stimulus parameters affecting visually-induced vection

Vection induced by moving visual stimuli has clearly received the most research attention so far and will thus be discussed in more detail below. Self-motion illusions can, however, also be induced by other modalities including auditory (see reviews by Riecke et al., 2009; Väljamäe, 2009), tactile (Dichgans & Brandt, 1978), or biomechanical cues (Bles, 1981; Brandt et al., 1977) or from direct galvanic stimulation of the vestibular system (Cress et al., 1997; Lepecq et al., 2006). In the following, I will review different factors that have been shown to facilitate vection, and how they might be utilized in VR and other immersive situations. Note that this information can, of course, equally be used to inhibit self-motion illusions were desired to avoid possible undesired side-effects, as discussed in section 6.

3.1 Up to an optimal velocity, higher stimulus velocities yield stronger vection

Higher stimulus velocities in general enhance vection, indicated by earlier vection onset, higher perceived self-motion velocity, and increased intensity and convincingness of the self-motion illusion (Allison et al., 1999; Brandt et al., 1973; Dichgans & Brandt, 1978; Schulte-Pelkum et al., 2003; Howard, 1986). For example, Brandt et al. (1973) showed that circular vection velocity increased linearly with increasing stimulus movement up to 120°/s and roughly matched the stimulus velocity. Further increasing stimulus velocity did not increase perceived self-rotation velocity further, such that the moving stimulus was no longer perceived to be earth-stationary. In terms of VR applications, this suggests that there might be maximum movement and/or optic flow velocities beyond which simulation effectiveness could deteriorate and the simulated world might no longer be perceived as stable.

3.2 Larger stimulus sizes increase vection

One major factor determining the onset and strength of vection is the solid angle (field of view, FOV) subtended by the moving visual stimulus. Although stimulus sizes as small as 7.5° have been shown to induce linear vection under carefully designed lab conditions (Andersen & Braunstein, 1985), larger stimulus sizes generally enhance vection in all measures, and full-field stimulation results in the strongest vection to a point where it cannot be suppressed any more and can be indistinguishable from actual self-motion (Berthoz et al., 1975; Brandt et al., 1973; Dichgans & Brandt, 1978; Held et al., 1975).

3.3 Central and peripheral vision is equally effective in inducing vection

While earlier studies reported that peripheral visual motion is more effective in inducing vection than central motion (Brandt et al., 1973; Dichgans & Brandt, 1978; Johansson, 1977), later studies demonstrated that peripheral and central motion have similar influences on vection when their display areas are equated (Andersen & Braunstein, 1985; Howard & Heckmann, 1989; Nakamura, 2008; Post, 1988; Wolpert, 1990). In fact, the peripheral dominance effect observed earlier was likely caused by peripheral stimuli being perceived as farther away than central stimuli. When perceived depth is held constant, vection strength linearly increases with increasing stimulus size, independent of stimulus eccentricity (Nakamura, 2008).

3.4 Optimal spatial frequency for vection depends on stimulus eccentricity

There is, however, an interaction between optimal frequency for central versus peripheral stimulation: Palmisano & Gillam (1998) showed that the most compelling circular vection is achieved when lower spatial frequency patterns are presented peripherally (where the eye's spatial resolution is also lower) and higher-spatial frequency stimuli are presented to central vision (where acuity is higher). From an applied perspective of improving self-motion simulations, the decreased peripheral sensitivity to high-frequency stimuli relaxes the need for high-resolution displays or imagery in the periphery unless the user needs to focus there (see also discussion in Wolpert, 1990). Even without a central display, vection can be reliably induced by peripheral stimulation: Brandt el al. (1973) demonstrated that circular vection was hardly reduced when the central 120° of the human visual field was blocked and participants saw motion only in the far periphery. Similar amounts of vection were achieved when visual motion was restricted to a horizontal streak of 60° height and full-field width. These results suggest that adding affordable low-resolution displays in the periphery of VR or other immersive setups might have surprisingly strong effects on perceived self-motion (and likely also presence and immersion).

3.5 Density of moving contrasts enhances vection

While single moving dots or objects can hardly induce vection, increasing their number and density can eventually induce vection, and vection strength seems to generally increase with the density of moving contrasts (Brandt et al., 1975; Dichgans & Brandt, 1978). Thus, care needs to be taken for simulations where there are only few objects (e.g., for flight, space, or diving simulations), especially if they are also far away (and thus have low image velocity for translations). If compelling vection is desired, it might thus be necessary to carefully add nearby objects to increase overall optic flow and relative motion with respect to stationary foreground objects. Ideally, this should be done in the context of the simulation scenario to ensure ecological validity. For flight simulations, this could, e.g., be achieved by adding clouds or haze.

3.6 Linear vs. circular vs. curvilinear vection

Trutoiu et al. (2009) demonstrated that linear vection in a panoramic projection setup was less convincing than circular vection, whereas curvilinear vection was perceived to be as convincing as circular vection. This has interesting implications for motion simulations, suggesting that even slight curvatures in the path might be able to increase the convincingness of the motion percept. Linear vection could be enhanced by adding a floor projection, though, possibly due to the special role that a perceivable moving ground plane seems to play in vection (Sato et al., 2007).

Overall, however, up-down (aka “elevator”) vection tends to be more compelling and occur earlier than left-right or forward-backward vection, likely because up-down movements do not change the direction of the gravito-inertial vector, such that accelerational and gravitational forces are parallel (Giannopulu & Lepecq, 1998; Trutoiu et al., 2009). Similarly, continuous circular vection around the earth-vertical axis can be induced more easily than vection around earth-horizontal axes (roll or pitch). The latter can lead to paradoxical sensations of limited body tilt despite continuous sensations of tilting (Allison et al., 1999; Held et al., 1975; Young et al., 1975). This has been attributed to the conflict between the visually-suggested tilt in the gravitoinertial vector and the actual gravitoinertial vector (sensed by the otoliths in the vestibular system and the somatosensory system) which does not tilt. Without full-field stimulation and a naturalistic visual stimulus, it seems difficult to obtain pitch or roll vection that includes head-over-heels orientations. As most real-world situations do not include those extreme orientations, this might not be a major limitation for most VR and immersive media applications, though.

3.7 Simulated viewpoint jitter facilitates vection despite visuo-vestibular conflict

Traditionally, it was often believed that vection should be facilitated if the sensory conflict between visual cues (simulating motion) and vestibular cues (indicating stationarity) was reduced. This view is supported by findings that bilaterally labyrinthine defective participants perceive visual vection much earlier and more intense (Johnson et al., 1999), and can perceive unambiguous roll or pitch vection through head-over-heels orientations (Cheung et al., 1989). In a series of studies, Palmisano and colleagues challenged this notions by showing that forward linear vection occurred earlier, lasted longer, and was more compelling when coherent viewpoint jitter was added to the expanding optic flow display (Palmisano et al., 2000), whereas incoherent jitter impaired vection (Palmisano et al., 2003). Moreover, viewpoint jitter alone induced weak vection sensations, without any overall radial or lamellar optic flow (Palmisano et al., 2003).

3.8 Perceived rigidity of optic flow field enhances vection

Nakamura (2010) extended these findings in showing that coherent visual jitter can facilitate linear vection even when the stimulus does not contain any depth cues and appears flat, whereas incoherent jitter impaired vection. Nakamura proposed that coherent jitter increasing the perceived rigidity of the random dot display, which in turn facilitated vection. Increasing the perceived rigidity of a vection-inducing stimulus seems, however, not to be the only mechanism underlying the vection-facilitating effect of stimulus jitter, as the effect can also be observed for naturalistic stimuli, which are arguably readily perceived as inherently rigid: Using videos of translations along a hallway, Bubka & Bonato (2010) showed that adding image oscillations induced by walking motions considerably enhanced linear forward vection strength while reducing vection onset latencies. Similar facilitation of forward linear vection when including slow viewpoint oscillations has been reported for more abstract optic flow displays (Palmisano et al., 2007). Surprisingly, it did not matter whether the viewpoint oscillations were caused by active head oscillations or just passively viewed without any head motions (Kim & Palmisano, 2008).

While it is tempting to suggest to add coherent image jitter or oscillations to VR simulations in order to enhance self-motion perception and perceptual realism, this should be carefully evaluated on a case-by-case basis, as adding image jitter/oscillations has also been shown to increases motion sickness (Palmisano et al., 2007), likely due to the increased sensory conflict between visual and non-visual cues.

4. Beyond physical stimulus parameters: How we look at, perceive, and interpret the stimulus can also affect vection

As described above, previous vection research mostly focussed on how various physical parameters of the moving stimulus like the stimulus contrast or field of view affect vection via lower-level, bottom-up perceptual processes. As I will argue in this section, there is, however, increasing evidence that vection can also be affected by what is outside of the moving stimulus itself, by the way we move and look at a moving stimulus, our pre-conceptions, intentions, and how we perceive and interpret the stimuli. Vection might even be directly or indirectly affected by higher-level and cognitive/top-down processes (Andersen & Braunstein, 1985; Lepecq et al., 1995; Mergner & Becker, 1990; Riecke et al., 2005). While many of these findings are exploratory in nature and await further careful experimentation, they provide a fascinating glimpse into the complex processes and interactions underlying the phenomenon of perceived self-motion without actual self-motion. Apart from its theoretical relevance, potential higher-level/cognitive/intentional contributions to vection might be of considerable interest for many applications, as these factors can often be manipulated with relatively small effort and cost.

4.1 Eye movements and relative motion perception

Intent and eye movements: Fixation and staring facilitate vection, as compared to smooth pursuit

In the following, I will review research demonstrating that vection is not only determined by the physical parameters of the moving stimulus (i.e., strictly bottom-up perceptual processes), but also strongly influenced by our intent and specifically the way we look at a moving stimulus. When viewing a moving visual stimulus without explicit viewing instruction, our eyes smoothly follow the stimulus (optokinetic nystagmus). Likely one of the first observations on vection-facilitating factors was that fixating on a stationary foreground object (like our outstretched hand) facilitated vection (Fischer & Kornmüller, 1930; Mach, 1875; Wallach, 1940; Warren, 1895). However, fixation is not necessarily required, and inattentively staring at a moving pattern can also facilitate vection (Fischer & Kornmüller, 1930). Careful experimentation by Becker et al. (2002) showed that suppressing the optokinetic reflex by fixating a stationary fixation point yields higher perceived vection velocities and lower vection onset latencies, as compared to trying to suppress the optokinetic reflex without a fixation point or merely staring at the stimulus. Attentively following the moving pattern yielded the lowest vection velocity and highest onset latencies, although eye movements were similar to the staring condition. This suggests that not only retinal slip and the pattern of eye movements, but also one's intent (e.g., to follow vs. stare) can affect self-motion illusions, as has been shown and mathematically modeled in a series of studies (Becker et al., 2002; Mergner et al., & Becker, 2000; Mergner et al., 2000).

In terms of applications like motion simulations, differences in the user task, instructions, and intentions could thus have a considerable effect on the perceived self-motion and consequently on the overall believability and effectiveness of a simulation. For instance, instructions that require users to fixate on foreground objects moving with the observer instead of the simulated outside scene (e.g., checking the speedometer or operating the radio in a car or aircraft cockpit instead of looking at the surrounding outside environment) might somewhat surprisingly enhance self-motion perception and thus potentially overall simulation realism and effectiveness.

Note, however, that the combination of fast-moving stimuli and a limited update rate (typically 60Hz) of VR displays can induce undesirable perceptual artifacts like flicker and ghost images, especially when observers fixate or stare at the display and thus do not follow the visual motion with their eyes. Moreover, color-sequential displays like 1-chip dlp projectors or the commonly-used LCoS head-mounted displays (HMDs) can induce color separation for fast-moving sharp contrast edges, even without fixation or staring. Thus, applications where fast object or observer motion is required should be carefully tested and tuned to limit display artifacts.

Increasing retinal slip, local image velocities, and relative motion between moving stimulus and observer-fixed reference frame facilitates vection

Apart from fixation and staring, peripheral looking and gaze shifts between central and peripheral regions can also improve forward linear vection (Palmisano & Kim, 2009). Potential factors underlying this effect include faster local image velocities and increased retinal slip (local image velocity is higher in the periphery for radially expanding flow fields) as well as screen boundary effects as described in the following. Several studies demonstrated that vection depends not only on characteristics of the moving visual stimulus itself, but also on the relative motion between the moving visual stimulus and stationary reference objects. For example, circular vection was facilitated when the moving visual stimulus was surrounded by a stationary rectangular foreground viewing window (Howard & Heckmann, 1989). Merely adding two vertical thin bars as stationary foreground objects also enhanced vection, in particular for slowly (5°/s) moving stimuli where vection is otherwise hard to achieve (Howard & Howard, 1994). Howard and colleagues argued that the effect originated from the relative motion signal between the stationary foreground objects and the moving stimulus, although it seems that perceived object-background separation might also have contributed (Seno et al., 2009, see also subsection below). Even without physical depth separation, stationary objects can facilitate vection, as was shown by Lowther & Ware (1996) when adding a rectangular 5×5 grid to a projection screen displaying the moving stimulus or by Riecke et al. (2005, exp. 2) when adding hardly noticeable marks (scratches) to the projection screen.

This opens up interesting avenues and future research areas for facilitating vection in non-obtrusive ways, without the need for fixation or other restrictions of eye movements. Especially for slow image motions, adding a stationary (foreground) reference frame can provide relative motion cues that facilitate motion detection and vection. This can be achieved, e.g., though the frames of multi-monitor setups, through real or simulated window frames (like the windscreen pillar in driving or flight simulators), or through other means that should ideally be inspired by and match the motion metaphor and application scenario. Ironically, although large-FOV spherical or cylindrical projection setups have many advantages, they typically provide only limited relative motion cues due to the lack of visible screen boundaries or other foreground objects, which can reduce their vection-inducing potential.

4.2 Perceived background motion, not just physical depth determine vection

Already in 1975, Wist et al. (1975) demonstrated that the perceived self-rotation velocity (which is often used as a measure of the strength of circular vection) increases not only with the angular velocity of the visual stimulus as one might expect, but also linearly increases with the perceived distance of the moving stimulus. However, later research demonstrated that not only the absolute perceived distance, but in particular the relative depth structure and figure-ground (or object-background) separation seems critical, in that the stimulus that is *perceived* to be further away typically determines the occurrence, direction, and strength of vection (Brandt et al., 1975; Howard & Heckmann, 1989; Ito & Shibata, 2005; Nakamura, 2008; Nakamura & Shimojo, 1999; Ohmi & Howard, 1988; Ohmi et al., 1987). Several of these studies used perceptually bistable displays and demonstrated that not only physical stimulus parameters themselves, but in particular how the stimulus is perceived and interpreted at any moment in time can modulate or even determine self-motion perception. For example, monocular viewing of two optic flow displays in Ohmi et al. (1987) caused spontaneous reversals in their perceived depth order, without any physical stimulus changes. Results showed that the display that was currently perceived to be the further away dominated the self-motion percept, irrespective of the physical depth order and irrespective of which of the two displays was fixated or pursued.

Importance of perceived object-background relation for vection

As our visual system readily organizes visual stimuli into figure versus ground (i.e., perceptual objects versus background), the findings by Ohmi et al. (1987) could be interpreted as the perceived background dominating vection, whereas "figures" (e.g., objects in the foreground) having less, if any, effect on vection (Kitazaki & Sato, 2003; Ohmi et al., 1987). This hypothesis was confirmed and extended in a clever series of experiments by Seno et al. (2009), who used two independently moving luminance-defined gratings organized to form perceptually bistable displays like a Rubin's vase that show spontaneous reversals of the figure-ground (i.e., the object-background) relationship. When a moving stimulus was currently perceived as an "object", it's vection-inducing potential decreased to a point where it could no longer induce vection. Conversely, the part of the stimulus that was currently perceived as the "ground" or background determined vection responses, even if it was stereoscopically defined to be closer than the "object". Moreover, Experiment 5 of Seno et al. (2009) showed that upright shapes (face, apple, or human figure) produced stronger vection than inverted (upside-down) shapes, arguable because the inverted shapes were less likely to be perceived as an object.

Object-background and rest frame hypothesis provide a unifying framework

Seno et al. (2009) proposed that the object versus background hypothesis could provide a unifying framework for investigating and better understanding vection and vection-inducing stimuli. In particular, many factors that have been shown to facilitate vection are also typical properties of the perceived background, like occupying a large field of view, peripheral stimulation, lower spatial frequencies, rigidity and coherent visual motion, being a ground plane, being unattended, or being further away than other parts of the display. For example, paying particular attention to one of the two motion components in Kitazaki & Sato (2003) might have emphasized it's "object" or "foreground" status, such that other aspects of the stimulus were more likely to be perceived as a background and thus dominated vection. Similarly, fixating a stationary part of the display might have perceptually enhanced its object-likelihood, such that the other (now "background") stimulus dominated vection.
Note that the object-background hypothesis bears similarity with the *rest frame hypothesis* proposed earlier by Prothero (1998) and Prothero & Parker (2003). This hypothesis states that "a particular reference frame, the 'rest frame,' is selected as the comparator for spatial judgments" (Prothero & Parker, 2003, p. 47). In this sense, spatial presence as well as vection are proposed to be (in part) determined by the extent to which a presented stimulus is accepted and selected as a primary reference or rest frame, which in turn is related to the likelihood of it being perceived a as background (see also theoretical framework by von der Heyde & Riecke, 2002; Riecke, 2003, chap. IV).
The findings by Riecke et al. (2006) could also be interpreted in the context of the object-background hypothesis and rest frame hypothesis: They observed that vection was reduced when the naturalism of the visual stimulus was decreased by inverting the presented scene or making it globally inconsistent via scene scrambling (see section 4.6 for details). Both stimulus inversion and scrambling decreased spatial presence and arguably might also have reduced the likelihood that the moving stimulus was perceived as a background and accepted as a stable reference frame with respect to which visual motion is more likely to be interpreted as self-motion rather than object-motion. In particular, I propose that spatial presence and immersion in a real or simulated environment are tightly linked to the likelihood of the stimulus being perceived and accepted as a "background" or scene. That is, in order for strong spatial presence and immersion to emerge, the visual stimulus should not be perceived as an object, but instead as a scene or background that can act as a stable reference or rest frame (von der Heyde & Riecke, 2002; Prothero, 1998; Prothero & Parker, 2003; Riecke, 2003, chap. IV). Although further research is needed to explore the concept of perceptual object-background separation and rest/reference frames for vection, the simplicity and unifying nature of these concepts if promising and might ultimately enable a deeper understanding of the underlying processes and allow us to better predict how vection and other phenomena like spatial presence depend on various stimulus parameters.

Stationary foreground vs. background

In agreement with the object-background hypothesis and the rest frame hypothesis, adding stationary background stimuli has been found to reduce or even inhibit circular vection, especially when presented peripherally, whereas stationary foreground stimuli can facilitate circular vection, especially if centrally presented (Brandt et al., 1975; Howard & Howard, 1994; Nakamura, 2006). Moreover, stationary foreground stimuli in front of a moving background are typically perceived to be moving with the observer, suggesting they are localized in body coordinates (Brandt et al., 1975; Fischer & Kornmüller, 1930), whereas during saturated vection the moving background stimulus is perceived as stationary in external coordinates and thus might act like an allocentric reference frame or rest frame. This situation is similar to riding a vehicle, where close-by objects (being part of the vehicle) move with the observer and are thus likely represented in an egocentric (body-centered) reference frame, whereas the more distant (outside) stimuli are likely to be part of the stationary environment. This can easily be utilized in motion simulator design and other applications (Nakamura, 2006). If the goal is to enhance perceived self-motion and overall realism, providing centrally located physical foreground objects like a cockpit, instruments, or other objects that match the overall simulation/application metaphor would be instrumental. This way, the simulated scene (outside of the cockpit) will be more easily perceived as the background, thus facilitating vection and enhancing overall simulation effectiveness. Conversely, if desired, vection (and potentially also motion sickness) can be reduced or even suppressed by providing peripheral static backgrounds (Prothero & Parker, 2003). Incidentally, this mimics typical desktop VR/gaming situations, where the static visible background of the room typically suppresses self-motions that might otherwise occur from the visual motions presented on the centrally located monitor in the foreground.

4.3 Consistent stereoscopic depth cues facilitate vection

Displaying the vection-inducing stimulus stereoscopically has been shown to facilitate both circular and linear vection (Lowther & Ware, 1996; Palmisano, 1996). Furthermore, consistent stereoscopic cues can increase the speed and travelled distance for optic flow-induced linear forward vection, which might have mediated the vection-enhancing effect of stereoscopic cues (Palmisano, 2002). Palmisano argued that the vection-enhancing effect of stereoscopic presentation goes beyond merely increasing the perceived distance of the visual stimulus. With stereoscopic presentation becoming increasingly available and affordable, this opens up new opportunities for increasing vection and the overall simulation experience by not only providing stereoscopic information of the simulated scene, but also purposefully enhancing object-background separation, providing unobtrusive stationary foreground object that increase the relative perceived motion between the stationary (observer-fixed) foreground and background movement through the simulated scene, or by providing a more realistic and believable scene that can more easily be accepted as a primary reference or rest frame.

4.4 Head-tracking can facilitate vection for moving observers

Lowther & Ware (1996) demonstrated that vection occurs later when observers moved in front of the stationary display used to present the vection-inducing motion, possibly because of the increased cue conflict between visual and vestibular/somatosensory cues. Using head tracking to couple the simulated perspective to the observers' motion mitigated most of the motion-induced vection deterioration.

This highlights the importance of including head tracking whenever observer head position is not fixed, such as to provide a simulated scene that "behaves" like the real world and can be perceived as stable in 3D space despite head movements. Head tracking might have facilitated vection by stabilizing the simulated scene, thus making it more believable and increasing the likelihood that it is selected and accepted as a primary reference frame or rest frame with respect to which scene relative motions are more easily perceived as self-motion instead of object-motions (von der Heyde & Riecke, 2002; Prothero & Parker, 2003; Riecke, 2003, chap. IV).

4.5 Attention and cognitive demand can modulate vection

To investigate potential attentional biases in visual vection, Kitazaki & Sato (2003) presented participants with vertically moving patterns of red and green dots moving in opposite (up vs. down) direction, and asked participants to attend to either the red or the green dots. The perceived direction of vection was largely determined by the non-attended stimulus, both when the red and green dots were spatially separated (exp. 1) or superimposed (exp. 2). When the upward and downward moving patterns were presented in different depth planes, however, the far stimulus dominated the attentional modulation, although there was still some attentional contribution. Apart from a direct effect of attention on vection, it is also conceivable that the attended stimulus was perceived to be closer, such that perceived depth ordering and not attention per se determined vection (see discussion in Seno et al. 2009). Furthermore, the attended stimulus might have become the perceptual "object" or "figure", such that attention might have modulated the perceptual object-background relationship, which in turn might have determined vection. Recently, Trutoiu et al. (2008) showed that forward linear visual vection occurs earlier if participants were performing an attention-demanding working-memory task (counting specific targets moving by in the visual stimulus). This suggests that vection can be enhanced if one does not pay particular attention to the vection-inducing stimulus.

In summary, although it seems likely that attention can modulate vection, it remains to be determined if attention can directly affect vection or whether the effect is mediated by other factors like eye movement patterns or changes in the perceived depth structure or object-background relationships. No matter what the underlying processes, it is clear that we can modify the vection experience intentionally to some degree, which is relevant for both fundamental research, where task instructions should be carefully phrased, and for applications, where task requirements and expectations can likely affect the effectiveness of a motion simulation and the overall user experience.

4.6 Reference frames, naturalism, and ecological validity of vection-inducing stimuli

Already in 1954, Gibson put forth that "Perceived motion occurs in a perceptually stable space or environment. Another way of saying this is to assert that the perception of stability is part and parcel of the perception of motion; you cannot have the latter without the former" (Gibson, 1954, p. 310). Thus, when we see environmental motion, (illusory) self-motion might be inferred due to our conscious or unconscious assumption of a stable environment (Dichgans & Brandt, 1978; Prothero & Parker, 2003). If this were the case, one might posit that moving visual or auditory stimuli that depict objects that normally do not move (e.g., houses or the sound of church bells) should enhance vection, compared to moving objects where our experience does not suggest stationarity (e.g., the sight or sound of a moving car). In the following, I will review studies that explicitly tested this hypothesis for visual vection. Note that auditory vection can also be facilitated when the moving sound sources represent objects that normally do not move (so-called "acoustic landmarks" like church bells) as compared to objects that move (e.g., the sound of a driving car) or are ambiguous (e.g., pink noise) (Larssonet al., 2004; Riecke et al., 2005; Väljamäe et al., 2009).

While most of the classic visual vection studies used abstract stimuli like polka-dotted or striped patterns, several researchers stressed that complex, naturalistic, and ecologically relevant stimuli should instead be used for studying self-motion perception (Gibson, 1954; Wann & Rushton, 1994). Indeed, when using naturalistic stimuli projected on a wide (142° × 110°) FOV dome projection of a flight simulator, van der Steen & Brockhoff (2000) observed surprisingly rapid vection buildup with saturated linear (forward) and circular (yaw) vection after only 2.7s and 3s, respectively. This is considerably faster than for abstract, non-naturalistic stimuli, where vection takes between 10s (Brandt et al., 1973) to 20-30s (Howard & Howard, 1994) until reaching saturation. This led van der Steen & Brockhoff (2000) to propose that the natural scene might have contributed to the unusually fast vection buildup. Unfortunately, this hypothesis was not directly tested, and a multitude of differences in the experimental setup, procedure, and response measures compared to classic vection studies makes direct comparisons problematic.

Naturalistic, globally consistent stimuli facilitate vection

To provide a more conclusive answer and assess if naturalistic stimuli do indeed enhance vection, we performed a series of experiments that directly manipulated the degree of naturalism and global scene consistency (i.e., higher-level factors) within one experimental paradigm (Schulte-Pelkum et al., 2003; Riecke et al., 2006). In a first study, circular yaw vection was induced by seating participants behind a curved projection screen (84°×63° FOV) displaying a rotating virtual environment created from either a naturalistic roundshot photograph (see Figure 1b) or a mosaic-like scrambled version of the same photograph (see Figure 1c)(Schulte-Pelkum et al. 2003, see also Schulte-Pelkum 2007, exp. 1). While the globally consistent scene was rendered perspectively correct and contained ample pictorial depth cues and might thus facilitate vection by providing a reference frame of a naturalistic environment on could feel spatially present in, the scrambled stimulus contained the same local image information and statistics, but could not be interpreted as a naturalistic scene one could feel present in. In addition, the scene scrambling procedure introduced additional high-contrast edges, which are known to increase perceived motion and facilitate vection (Dichgans & Brandt, 1978; Diener et al., 1976; Palmisano & Gillam, 1998). These lower-level factors thus worked against our higher-level hypothesis that naturalistic stimuli might enhance vection. Nevertheless, the naturalistic stimulus resulted in earlier vection onset and higher perceived vection intensity and convincingness than the scrambled stimulus.

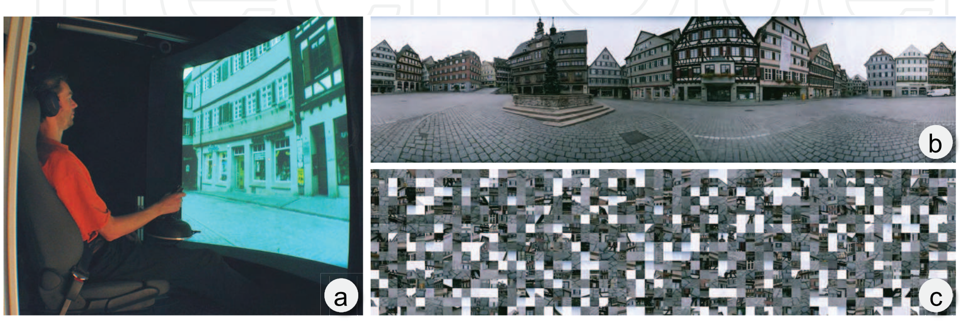

Fig. 1. (a): Participant seated behind curved projection screen showing the naturalistic circular vection stimulus based on a panoramic image (b). A globally inconsistent scene was created by mosaic-like scrabbling of the panoramic image (c).

Riecke et al. (2006) replicated and extended these results by systematically varying the degree of stimulus degradation and global inconsistency (see Figure 2, a-f). Results showed enhanced vection and presence for the naturalistic stimulus as compared to any of the sliced or scrambled stimuli, and hardly any influence of the type or degree of stimulus degradation. Figure 2, g-i contrasts the vection measures for the intact versus the least degraded stimulus. Together, these results suggest that higher-level factors related to scene consistency dominated over lower-level factors (more high-contrast edges for the scrambled stimulus) that would have predicted the opposite result.

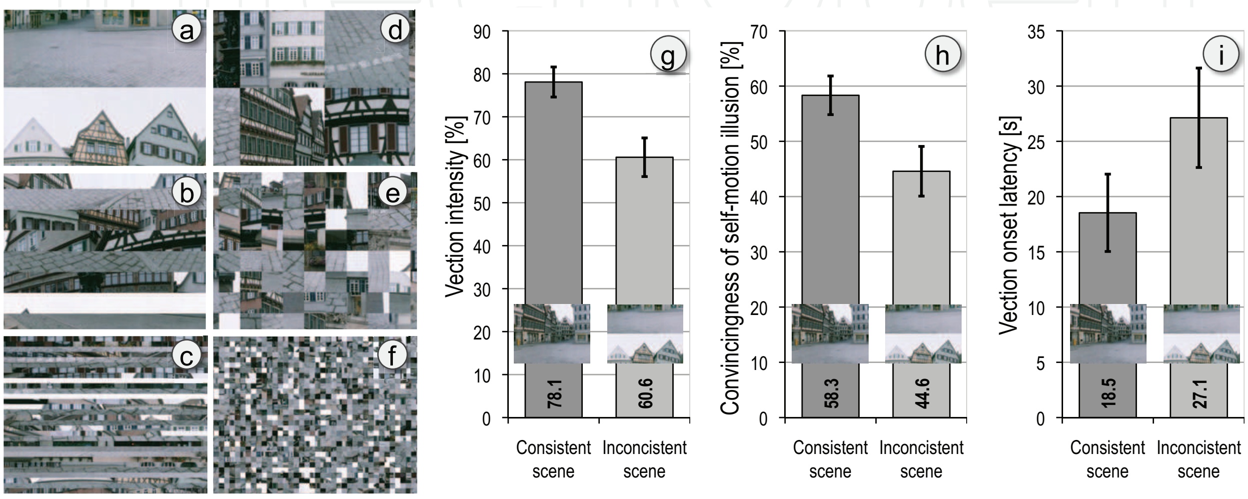

Fig. 2. 54°×45° view of the different horizontally sliced (a-c) and mosaic-like scrambled (d-f) vection-inducing stimuli as seen by participants in (Riecke et al., 2006) in addition to the globally consistent stimulus (cf. Figure 1, a & b). (g) – (i): Circular vection measures for the comparison of the globally consistent stimulus (left bar) and one of the globally inconsistent stimuli (the sliced version depicted in (a)). Note the vection impairment for the globally inconsistent (less naturalistic) stimulus, suggesting higher-level/cognitive influences. Depicted are mean ± one standard error of the mean, re-plotted from a subset of the original data of Riecke et al. (2006) for 40°/s stimulus velocity without data normalization.

There are at least three underlying mechanism that might explain the observed vection-facilitating effect of globally consistent, naturalistic stimuli:

1. The globally consistent stimulus contained ample pictorial depth cues arranged in a consistent, naturalistic environment. This might have increased the perceived distance of the stimulus, which is known to increase perceived vection velocity (Wist et al., 1975), which in turn is associated with enhanced vection. In fact, increasing stimulus velocities in (Schulte-Pelkum et al., 2003) from 20°/s to 40°/s to 60°/s reduced vection onset latencies and increased vection intensity and convincingness.
2. Previous studies showed that perceived foreground-background separation can affect vection: When vection-inducing stimuli are comprised of multiple parts (e.g., superimposed or spatially separated), vection is dominated by the motion of the perceived background (Howard & Heckmann, 1989; Nakamura & Shimojo, 1999; Ohmi et al., 1987; Seno et al., 2009). In our study, the naturalistic scene stimulus and pictorial depth contained therein might have resulted in a perceived foreground-background separation between the physical screen and setup acting as the foreground and the

projected scene being perceived as further away and thus acting as a moving background, thus indirectly facilitating vection.

3. Presence ratings were significantly higher for the naturalistic stimulus than any of the sliced or scrambled stimuli, and were consistently correlated with vection measures. Thus, the naturalistic scene might have provided a more believable and convincing, stable reference frame and primary rest frame than the globally inconsistent stimuli, such that stimulus motion might be more easily perceived or interpreted as self-motion than image or object motion (Dichgans & Brandt, 1978; Gibson, 1954; Prothero, 1998).

In sum, the data suggest that not only lower-level factors, but also higher-level factors like the interpretation of the stimulus as a believable and ecologically valid scene can affect self-motion perception.

Natural stimulus orientation enhances vection and presence

In a second experiment, Riecke et al. (2006) showed that inverting the naturalistic scene such that it appears upside-down reduced both the convincingness of vection and rated presence in the scene. Note that lower-level factors (e.g., image statistics) and scene consistency were identical between the upright and upside-down stimulus. This corroborates the relevance of higher-level/cognitive factors like the ecological validity and naturalism of the stimulus and the existence of optic flow from a believable ground surface, which has been shown to facilitate vection (Sato et al., 2007).

Naturalistic stimuli induce stronger vection than abstract geometric patterns

Further indication of potential higher-level influences stem from Richards et al. (2004), who investigated how postural stability during linear treadmill walking is affected by different moving visual stimuli presented on a projection screen (FOV: 65°×48°). Body sway in roll and pitch direction was more pronounced for a simple textured room display that contained intrinsic upright orientation cues (i.e., visual polarity defined by room geometry and clearly distinguishable ceiling, walls, and floor) as compared to a black and white polka-dotted cylindrical room that had no intrinsic upright cues. Furthermore, the room environment were rated as perceptually more compelling and resulted anecdotally in more frequent and intense vection experiences and reduced vection drop-outs. This supports findings by Riecke et al. (2006) and Schulte-Pelkum et al. (2003) that consistent, naturalistic visual cues enhance vection. Similarly, Wann & Rushton (1994) observed stronger circular vection for a naturalistic 3D environment presented via HMD as compared to the 2D texture stripes of a simulated optokinetic drum. Note, however, that the room versus polka-dotted stimuli in Richards et al. (2004) and the 3D environment versus texture stripes in Wann & Rushton (1994) differed not only in terms of naturalism and inherent upright-direction, but also with regards to other factors that are known to affect vection and could thus have contributed to the observed effects, including their spatial frequency content and the number of moving contrasts (Diener et al., 1976; Palmisano & Gillam, 1998; Hu et al., 1997) or perceived depth and foreground-background separation (Howard & Heckmann, 1989; Seno et al., 2009).

Tumbling sensation (roll vection) is facilitated by cue-rich, naturalistic environment

Additional support for the importance of naturalistic 3D environments comes from tumbling room studies, where stationary observers are surrounded by an (empty or fully furnished) room that can be rotated around the observers' roll axis. The perception of body tilt and roll vection was facilitated by a number of factors including the availability of a visual frame of reference, objects with clear visual polarity (i.e., intrinsic "up" direction), rotation velocity of the tumbling room, and field of view (Allison et al., 1999; Howard & Childerson, 1994). With 30°/s rotation of a fully furnished room with ample visual polarity cues and unrestricted FOV, up to 80% of observers experienced strong tumbling sensations including head-over-heels (cartwheel) roll vection. Tumbling (roll vection) occurred less frequently for smaller rotational velocities (15°/s instead of 30/s) and reduced field of views. These results highlight the vection-inducing power of naturalistic full-field visual motion. Further, carefully conducted research is, however, needed to more deeply understand what parameters of the visual stimulus make it more effective, and to disambiguate lower-level, bottom-up factors (like number of moving contrasts and edges) from higher-level perceptual and cognitive factors (like the "known" visual polarity of objects or the familiarity of "rooms"). Using wide-FOV VR simulators would give us the flexibility to more easily investigate these issues without the need to equip physical tumbling rooms with different objects and having to secure them for roll rotations.

4.7 Does the possibility of actual motion affect the illusion of self-motion?

Whenever self-motions are only simulated (e.g., through visual cues or a motion platform) and not actually performed, there is a conflict between some cues suggesting self-motion and others indicating stationarity. Apart from sensory cues directly indicating motion or no-motion, there are typically also other factors that might affect perceived self-motion. In particular, we are typically aware whether actual motion is, in fact, possible (e.g., when sitting on a moveable platform or vehicle) or not (e.g., when we stand/sit on solid ground). Thus, in order to provide compelling sensations of (illusory) self-motion, we might not only need to overcome the sensory conflict between sensory information suggesting self-motion versus stationarity, but potentially also "convince" us that actual motion is indeed possible.

Theme parks have long recognized the importance of providing a cognitive-perceptual framework of movability, e.g., by guiding users of a star wars fun ride (at Disney's Hollywood Studio theme park) through a (fake) space-craft airport before entering the "space-craft", which is a motion platform carefully disguised as a space ship such that users are unaware of the actual motion limitations of the system. Apart from being entertaining and avoiding that visitors get bored while waiting for the next ride, providing such a scenario and suggesting movability of the space craft might help to prime visitors to expect actual motion and more easily accept and believe the motion simulation. Although such suspension of disbelief is frequently used in consumer-market applications like theme parks and video arcades, there is surprisingly little published research investigating whether providing a cognitive-perceptual framework of movability can not only increase user enjoyment and fun but also enhance the effectiveness and believability of self-motion simulations.

As providing a cognitive-perceptual framework of movability can often be created at much lower cost and effort than increasing the actual motion range of VR simulations, pursuing this question could be of considerable interest for many applications. In addition, it can extend our understanding of higher-level influences on vection, and in particular on the integration of multi-modal sensory cues with higher-level cognitive/perceptual information. In the following, I will review and discuss research that explicitly investigated whether the perceived possibility of actual self-motion can enhance vection, for example by designing for situational awareness of movability by providing a cognitive-perceptual framework suggesting the possibility of actual self-motion.

Participants are often seated on movable devices to facilitate vection

In order to suggest movability and facilitate vection, a number of vection researchers have seated participants on rotating chairs when investigating circular vection (Lackner, 1977; Väljamäe, 2009) or on moveable carts when studying linear vection (Berthoz et al., 1975; Lackner, 1977; Pavard & Berthoz, 1977; Andersen & Braunstein, 1985) and demonstrated the possibility of motion prior to the actual vection experiments. Andersen & Braunstein (1985, p. 124) stated, for example, that "several subjects in pilot studies and other observers had previously reported that the experience of self-motion was inhibited by the observation that they were in an environment in which they could not be physically moved". Surprisingly, however, none of the above-mentioned studies provided actual data that vection was indeed facilitated when participants were seated on a moveable chair or cart.

Children experience vection earlier when sitting on moveable platform

To the best of our knowledge, the first study that explicitly addressed this issue was conducted by Lepecq et al. (1995) with children of seven and eleven years. Half of the participants were seated on a chair with rollers ("movement possible" condition) and were demonstrated prior to the actual experiment how the chair could move. The other half of the participants were seated on a stationary chair ("movement impossible" condition) and shown that the chair could not be moved. Although participants were always stationary during the subsequent backward linear visual vection experiment, knowledge about the possibility of motion reduced vection onset latencies. The frequency of vection occurrences remained unaffected by this cognitive manipulation, though. Nevertheless, Lepecq et al. (1995) provided first evidence that the knowledge and prior experience that actual motion is possible could facilitate vection, suggesting higher-level, cognitive contributions.

Is there a similar effect of perceived movability on vection in adults, or are they less easily "fooled to believe"? There are only a few studies that investigated this issue in adults, and the results provide somewhat mixed evidence.

Self-motion-bias versus object-motion-bias instructions affect vection reporting

Palmisano & Chan (2004) used adult participants and a similar overall procedure as Lepecq et al. (1995) to investigate if linear forward linear vection induced by an optic flow display is modulated by creating situations were physical movements are possible vs. impossible. While the "movement possible" (or self-motion-bias) group was instructed to report the onset and offset of *self-motion* as in Lepecq et al. (1995), the "movement impossible" (or object-motion-bias) group in Palmisano & Chan (2004) was instructed to report the onset and offset of *object motion*, and vection was inferred when no object motion was reported. This object-motion-bias reduced the occurrence of vection reports as compared to the self-motion-bias, although vection onset latencies were unaffected by the cognitive manipulation. Note that these results differ from Lepecq et al.'s findings, where the cognitive manipulation affected the onset latency, but not the occurrence of vection. It is conceivable that the object-motion-bias introduced a criterion shift and response bias in favor of reporting object-motion. Moreover, trials with only partial vection, where object- and self-motion co-exist, would have been identified as vection trials for the self-motion-bias group but as no-vection trials for the object-motion-bias group. Hence, it remains unclear whether the cognitive manipulation in Palmisano & Chan (2004) did indeed affect perceived self-motion.

Elevator vection occurs earlier if actual motion is possible

In a vertical oscillatory ("elevator") vection study with adults, Wright et al. (2006) showed that participants who were seated in a vertical oscillator and shown prior to the actual experiment how they could be moved reported more compelling vection than participants who saw the same vection stimulus, but were sitting on a stationary chair in a different room. Vection amplitudes and onset latencies remained unaffected by the cognitive manipulation, though. To explain their data, Wright et al. (2006) proposed two dissociable factors underlying vection: One process determining the compellingness of vection that is susceptible to cognitive manipulations, and a second process primarily driven by visual (bottom-up) cues that mainly affects vection onset latencies and the extend of the self-motion illusion. Note that this distinction does not fit the data by Lepecq et al. (1995), where the cognitive manipulation affected the onset latency, but not the occurrence of vection.

Visual circular vection not facilitated if actual motion is possible

While by Lepecq et al. (1995) and Wright et al. (2006) found a significant facilitation of linear visual vection when participants were previously demonstrated that actual motion is possible, circular visual vection might be less affected by such cognitive manipulations (Schulte-Pelkum, 2007; Schulte-Pelkum et al., 2004): When participants were seated on a 6 degree of freedom Stewart motion platform and previously shown how the platform can move, 2/3 of them did indeed believe that they were physically moving in at least some of the trials where the platform was switched on (see Figure 3, middle), and many of them were fairly certain that actual motion occurred (see Figure 3, right). Nevertheless, vection reports were unaffected by this cognitive manipulation, and vection onset times, intensity, and convincingness were identical between movement-possible and movement-impossible trials. As discussed in detail in Riecke (2009) and Schulte-Pelkum (2007), the lack of a clear vection-facilitating effect of the cognitive manipulation might be due to a number of differences in experimental procedures, as compared to Lepecq et al. (1995) and Wright et al.

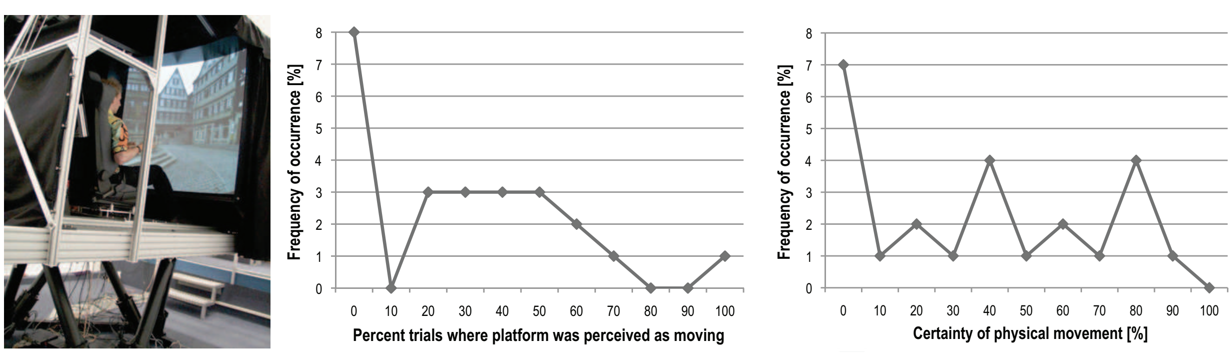

Fig. 3. **Left:** Participant seated on a motion platform that was either switched on ("motion possible" condition) or not ("motion impossible"). **Middle:** Histogram of participants' responses. Participants were asked to rate in what percentage of trials they perceived the platform to be physically moving. 8/24 participants (33.3%) stated that it never moved, whereas the remaining 66.7% stated that the platform moved in at least 10% of the trials. One participant stated that it always moved. **Right**: Participants were asked to rate how certain they were (on a 0-100% scale) that the platform did move in at least some trials. Only seven participants were certain that it never moved, and five participants were at least 80% certain that it moved. Data re-plotted from (Schulte-Pelkum et al., 2004; Schulte-Pelkum, 2007).

(2006), and we are currently planning experiments to assess if visual circular vection can indeed be affected by providing a cognitive-perceptual framework of movability.

Auditory vection can be facilitated by cognitive-perceptual framework of movability

While it remains to be demonstrated if a cognitive-perceptual framework of movability can affect visually-induced circular vection, there is recent evidence that it can affect auditorily-induced circular vection (Riecke, Feuereissen, & Rieser, 2009). In order to provide high-quality recordings of rotating sound fields for the auditory vection experiments, the lab was equipped with two easily distinguishable and localizable sound sources positioned 90° apart, and participants were seated on a hammock chair mounted above a circular treadmill (see Figure 4a) and passively rotated. Small in-ear microphones were used to generate individualized binaural recordings of what participants hear when actually rotating in the lab. During the subsequent vection experiment, participants sat on the hammock chair with the circular treadmill switched off while wearing blindfolds and noise-cancelling headphones displaying the previously recorded rotating sound fields. Participants' feet were either suspended by a chair-attached footrest (see Figure 4b, "movement possible" condition) or positioned on solid ground ("movement impossible" condition). Providing a cognitive-perceptual framework of movability in the "motion possible" condition yielded higher vection intensity ratings (see Figure 4d), and there was a marginally significant trend ($p<.1$) towards more frequent occurrence of vection (84% vs. 68%, see Figure 4c), reduced vection onset latencies (41s vs. 31s, see Figure 4e), and higher perceived realism of actually rotating in the lab. Hence, the common practice of seating participants on moveable chairs or platforms (Lackner, 1977; Väljamäe, 2007, 2009) does indeed seem to benefit auditory vection.

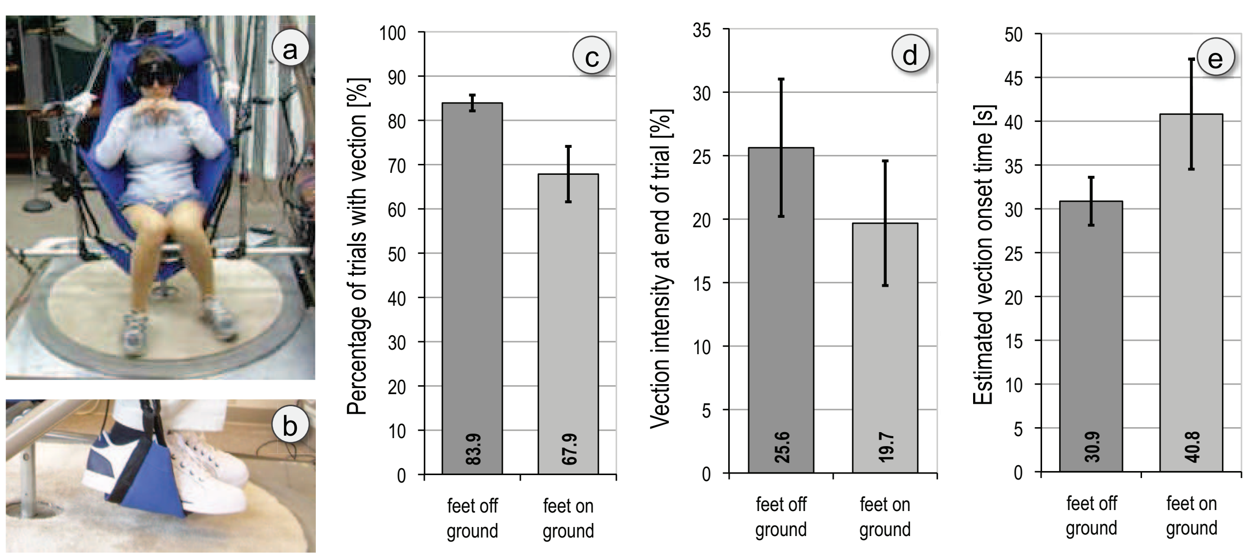

Fig. 4. (a): Participant wearing blindfold and noise-cancelling headphone, seated on a hammock chair mounted stationary above a circular treadmill. (b) In a "feet off ground" condition, participants' feet were suspended by a footrest, whereas in a "feet on ground" condition (a) participants' feet were on solid ground, thus acting as a "motion impossible" condition. (c) – (e): Auditory circular vection measures show slightly enhanced vection when participants' feet did not touch solid ground. Depicted are mean ± 1SEM, re-plotted from a subset of the original data of (Riecke et al., 2009) with no jitter.

The exact mechanisms underlying this effect await further experimentation, though: In the current experiment, both cognitive and perceptual factors might have contributed. On the one hand, resting one's feet on solid ground provides somatosensory and thus lower-level, perceptual cues indicating stationarity. On the other hand, it provides higher-level, cognitive "knowledge" that could have primed participants to believe that physical motion was impossible. From the current data, it is not possible to disambiguate between cognitive and perceptual factors, and they likely contributed both and might even support or depend on each other.

Touching the floor attenuates visual roll vection in weightlessness

The influence of touching the stationary floor on vection was also investigated by Young et al. (1983) and Young & Shelhamer (1990): While in weightlessness, visually induced roll vection was compared between a "free floating" condition, where only a bite bar fixated participants' orientation and position in space, and a "tactile" condition, where an additional shoulder harness pressed participants to the floor using elastic bands. Thus touching the floor resulted in more vection drop-outs and reduced the strength of roll vection. Some participants also reported prolonged vection onset latencies. Similar to the auditory vection study discussed above (Riecke et al., 2009) touching and being restrained to the floor in Young et al. (1983) and Young & Shelhamer (1990) might have attenuated visual roll vection via both lower-level perceptual processes, namely somatosensory cues indicating being tied to a stationary floor, and higher-level, cognitive factors like the knowledge that actual motion was impossible due to the restraints.

Conclusions

In summary, although it is often difficult to disentangle the possible influence of cognitive versus perceptual processes, there is converging evidence that providing a cognitive-perceptual framework of movability can under certain conditions facilitate self-motion perception. This is consistent with informal reports and common practice of seating participants on moveable platforms in situations where vection is difficult to achieve, as is the case for auditory vection (e.g., Lackner 1977; Väljamäe 2007) or visual vection with small field of views (Andersen & Braunstein, 1985). Although the above-mentioned results are promising, further research is necessary to enable us to more deeply understand why, how, and under which conditions perceptual and/or cognitive information suggesting movability versus stationarity can affect self-motion perception. While of clear theoretical interest, there is also a clear applied benefit, as cognitive-perceptual frameworks of movability can often be implement with relatively little effort, especially compared to the costs involved in allowing for large-scale physical locomotion or full-fledged motion simulators.

5. Cross-modal facilitation of vection

While an in-depth review of multi-modal aspect of vection would go beyond the scope of this chapter, it is important to realize that there are a number of cross-modal effects and facilitations of vection that could help to optimize VR simulations and other immersive applications. For example, galvanic vestibular stimulation can both directly induce self-tilt and affect visually simulated self-motions (Cress et al., 1997; Lepecq et al., 2006). Adding subtle vibrations to the observers' seat and footrest has been shown to enhance visual vection (Riecke et al., 2005; Schulte-Pelkum, 2007). Similarly, vibrations can enhance auditory vection (Riecke et al., 2009), especially if accompanied by a matching simulated engine sound (Väljamäe et al., 2006; Väljamäe et al., 2009). Although moving sound fields by themselves can only induce vection in about 20-75% of blindfolded listeners, they have been shown to enhance vection induced by other modalities, including visual circular vection (Riecke et al., 2009) and biomechanical circular vection induced by stepping along a circular treadmill (Riecke et al., 2010). Adding small physical motions (simple jerks) to the onset of visually simulated self-motion has been shown to significant enhance visually induced vection, both for passive movement (Berger et al., 2010; Riecke et al., 2006; Schulte-Pelkum, 2007; Wong & Frost, 1981) and for simple self-initiated motion cueing (Riecke, 2006). Note that these jerks facilitated vection despite being only qualitatively correct (i.e., they matched the direction and precise temporal onset of the visual motion, but not the extent or acceleration). This suggests that there might be a surprisingly large coherence zone within which visuo-vestibular conflicts go unnoticed or at least have little detrimental effect (Steen, 1998). Finally, applying vibrations and small physical movements (jerks) together enhanced visual vection more then either of them alone (Schulte-Pelkum, 2007, exp. 6). Together, these results suggest considerable cross-modal benefits for self-motion perception, even when cross-modal stimuli are only qualitatively matched. While proper motion cueing using 6DOF motion platforms is clearly desirable in many applications including flight or driving simulations, budgets and space are often limited. In such situations, vibrations and spatialized auditory cues can often be included at moderate cost and effort. Even simple commercially available motion seats or gaming seats might provide considerable benefits to self-motion perception and overall simulation effectiveness.

6. Potential undesirable side-effects of vection in VR

For all applications, the potential benefits of providing compelling self-motion illusions need to be carefully evaluated against potential undesirable side-effects (for a detailed discussion, see Hettinger 2002; Kennedy et al. 2003 and references therein). The occurrence of vection can, for example, correlate with undesirable side-effects like motion sickness or motion after-effects. It is, however, still unclear whether or how vection might be causally related to motion sickness, as vection generally seems to occur when visuo-vestibular cue conflicts are small, whereas motion sickness tends to occur for larger cue conflicts (Kennedy et al., 2003; Palmisano et al., 2007). Moreover, visually-induced motion sickness can occur without either vection or optokinetic nystagmus (Ji, So, & Cheung, 2009). Vection is also known to co-occur with body sway in standing observers (Howard, 1982). While small infants can indeed tip over due to large-field visual stimulation (Lee & Aronson, 1974), children older than five years and adults seem less affected and sway less. While vection and visually induced body sway likely share similar pathways and vection strength can be indicative of body sway, body sway occurs well before the onset of vection and does not necessarily match the direction of perceived self-motion, again questioning a direct causal relation between vection and body sway (Guerraz & Bronstein, 2008; Wang et al., 2010). In sum, further research is needed to carefully assess factors promoting undesirable side-effects like motion/simulator sickness, postural responses, after-effects, and (re)adaptation effects, and to what degree there might or might not be any causal relationships to vection.

7. Conclusions and outlook

Self-motion illusions are embodied illusions that can be quite compelling and thus critically affect the overall experience and effectiveness of VR and other immersive media. Hence, it is important to better understand the nature of the phenomenon of vection and the different contributing factors and their interactions, such that the illusion can be purposefully elicited or suppressed, depending on the specific goals and requirements of a given application. While this chapter provides a review on different factors that can enhance vection, this information can, of course, also be used to purposefully inhibit the illusion where desired. Depending on the goals and user task of an application, different degrees of vection and overall presence/immersion might be desirable, and it should be carefully evaluated on a case-by-case basis to what degree vection can or cannot contribute to the overall goal.

Given the increased availability and affordability of large, multi-screen displays setups, care should be taken that self-motion is only perceived where intended. For example, when manipulating 3D objects or CAD models on a screen, this should be perceived as object motion and not self-motion. Especially when users have to quickly switch between different tasks, screens, or simulated environments, vection as well as spatial presence and immersion should be avoided. Conversely, for architecture walkthroughs, vehicle simulation, telepresence, and other applications where perceptual/behavioral realism is of the essence, simulated observer motions should be perceived as self-motion and not object motion; else, the 3D model might be perceived as a small toy mockup instead of a full-sized, naturalistic environment. For disambiguating between perceived object versus self motion, manipulating the perceived object-background separation might be the most effective means, as discussed above.

Interestingly, many sought-after attributes in the design of VR systems and other immersive media seem to also be factors that are known to enhance vection, such as large FOVs, naturalistic and ecologically valid stimuli, stereoscopic presentation, perceived background motion, or multi-modal stimulation and consistency. In particular, presence in the simulated environment frequently correlates with vection, seems to benefit from similar factors as vection, and might even be mediated by vection (Riecke et al., 2006; Väljamäe, 2009), as predicted by the rest frame hypothesis (Prothero & Parker, 2003). I propose that utilizing and further developing promising comprehensive frameworks like the rest frame hypothesis (Prothero, 1998; Prothero & Parker, 2003), the object-background hypothesis (Seno et al., 2009), or the reference frame model (von der Heyde & Riecke, 2002; Riecke, 2003, chap. 4) can foster a deeper understanding of the mechanisms underlying phenomena like vection, presence, or spatial orientation and enable us to devise operation definitions and novel measurement methods (Prothero & Parker, 2003; Riecke, 2003, chapter IV). Ultimately, being able to integrate seemingly disparate findings into a conceptual framework will allow us to derive testable hypothesis and predictions that can guide future research and applications.

In conclusion, a growing body of evidence suggests that vection and overall simulation effectiveness is not only determined by physical stimulus parameters themselves, but also by other factors including how we look at, perceive, and interpret the stimulus, the perceived foreground-background separation, and a variety of higher-level phenomena like cognitive-perceptual frameworks of movability, naturalism and ecological validity, spatial presence, and reference/rest frames. Clearly, these factors deserve more attention both in basic research and applications. These factors might also turn out to be crucial especially in the context of VR applications and self-motion simulations, as they have the potential of offering an elegant and affordable way to optimize simulations in terms of perceptual and behavioral effectiveness. Compared to other means of increasing the convincingness and effectiveness of self-motion simulations like increasing the visual field of view or using a motion platform, higher-level factors can often be manipulated rather easily and without much cost, such that they might be an important step towards a lean and elegant approach to effective self-motion simulation. This is nicely demonstrated by many theme park rides, where setting up the proper cognitive framework and expectation (both highly cognitive factors) helps to draw users more easily and effectively into the simulation and into "believing". Thus, I posit that an approach that is centered around the perceptual and behavioral effectiveness and not only the physical stimulus realism is important both for gaining a deeper understanding in basic research and offering a lean and elegant way to improve a number of applications, especially in the advancing field of virtual reality simulations. This might ultimately allow us to come closer to fulfilling the promise of VR as a believable "window onto the simulated world", such that the virtual reality can be perceived and accepted as an alternate reality that enables natural and unencumbered human behavior.

8. References

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Technological advancement in graphics and other human motion tracking hardware has promoted pushing "virtual reality" closer to "reality" and thus usage of virtual reality has been extended to various fields. The most typical fields for the application of virtual reality are medicine and engineering. The reviews in this book describe the latest virtual reality-related knowledge in these two fields such as: advanced human-computer interaction and virtual reality technologies, evaluation tools for cognition and behavior, medical and surgical treatment, neuroscience and neuro-rehabilitation, assistant tools for overcoming mental illnesses, educational and industrial uses In addition, the considerations for virtual worlds in human society are discussed. This book will serve as a state-of-the-art resource for researchers who are interested in developing a beneficial technology for human society.

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