Chapter 9
An Integrative Approach to Presence and Self-Motion Perception Research

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Abstract This chapter is concerned with the perception and simulation of self-motion in virtual environments, and how spatial presence and other higher cognitive and top-down factors can contribute to improve the illusion of self-motion ("vection") in virtual reality (VR). In the real world, we are used to being able to move around freely and interact with our environment in a natural and effortless manner. Current VR technology does, however, hardly allow for natural, life-like interaction between the user and the virtual environment. One crucial shortcoming is the insufficient and often unconvincing simulation of self-motion, which frequently causes disorientation, unease, and motion sickness. The specific focus of this chapter is the investigation of potential relations between higher-level factors like presence on the one hand and self-motion perception in VR on the other hand. Even though both presence and self-motion illusions have been extensively studied in the past, the question whether/how they might be linked to one another has received relatively little attention by researchers so far. After reviewing relevant literature on vection and presence, we present data from two experiments, which explicitly investigated potential relations between vection and presence and indicate that there might indeed be a direct link between these two phenomena. We discuss theoretical and practical implications from these findings and conclude by sketching a tentative theoretical framework that discusses how a broadened view that incorporates both presence and vection research might lead to a better understanding of both phenomena, and might ultimately be employed to improve not only the perceptual effectiveness of a given VR simulation, but also its behavioural and goal/application-specific effectiveness.

Keywords Behavioural effectiveness • Cognitive factors • Experimentation • Framework • Higher-level factors • Human factors • Human-computer interfaces • Immersion • Perception-action loop • Perceptual effectiveness • Perceptually-Oriented Ego-Motion Simulation • Presence • Self-motion illusion • Self-Motion Simulation • Spatial Presence • Vection • Virtual environments • Virtual reality

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This chapter is concerned with the perception and simulation of self-motion in virtual environments, and how spatial presence and other higher cognitive and top-down factors can contribute to improve the illusion of self-motion ("vection") in virtual reality (VR). In the real world, we are used to being able to move around freely and interact with our environment in a natural and effortless manner. Current VR technology does, however, hardly allow for natural, life-like interaction between the user and the virtual environment. One crucial shortcoming in current VR is the insufficient and often unconvincing simulation of self-motion, which frequently causes disorientation, unease, and motion sickness (Lawson et al. 2002). We posit that a realistic perception of self-motion in VR is a fundamental constituent for spatial presence and vice versa. Thus, by improving both spatial presence and self-motion perception in VR, we aim to eventually enable perceptual realism and performance levels in VR similar to the real world. Prototypical examples that currently pose considerable challenges include basic tasks like spatial orientation and distance perception, as well as applied scenarios like training and entertainment applications. Users frequently get lost easily in VR while navigating, and simulated distances appear to be compressed and underestimated compared to the real world (Chance et al. 1998; Creem-Regehr et al. 2005; Ruddle 2013; Hale and Stanney 2014; Witmer and Sadowski 1998).

The specific focus of this chapter is the investigation of potential relations between presence and other higher-level factors on the one hand and self-motion perception in VR on the other hand. Even though both presence and self-motion illusions have been extensively studied in the past, the question whether/how they might be linked to one another has received relatively little attention by researchers so far. After a brief review of the relevant literature on vection and presence, we will present data from two experiments which explicitly investigated potential relations between vection and presence and indicate that there might indeed be a direct link between these two phenomena (Riecke et al. 2004, 2006a). In the last part of this chapter, we will discuss the theoretical and practical implications from these findings for our understanding of presence and self-motion perception. We will conclude by sketching a tentative theoretical framework that discusses how a broadened view that incorporates both presence and vection research might lead to a better understanding of both phenomena, and might ultimately be employed to improve not only the perceptual effectiveness of a given VR simulation, but also its behavioural and goal/application-specific effectiveness.

The origins of the work presented here were inspired by an EU-funded project on "Perceptually Oriented Ego-motion Simulation" (POEMS-IST-2001-39223). The goal there was to take first steps towards establishing a lean and elegant self-motion simulation paradigm that is powerful enough to enable convincing self-motion perception and effective self-motion simulation in VR, without (or while hardly) moving the user physically. This research was guided by the long-term vision of achieving cost-efficient, lean and elegant self-motion simulation that enables compelling perception of self-motion and quick, intuitive, and robust spatial orientation while traveling in VR, with performance levels similar to the real world. Our approach to tackle this goal was to concentrate on perceptual aspects and task-specific effectiveness rather than aiming for perfect physical realism (Riecke et al. 2005c). This approach focuses on multi-modal stimulation of our senses using VR technology, where vision, auditory information, and vibrations let users perceive that they are moving in space. Importantly, we broadened the research perspective by connecting the concepts of top-down or high-level phenomena like spatial presence and reference frames to vection research (Riecke 2011). It is well-known that quite compelling self-motion illusions can occur both in the real world and in VR. Hence, the investigation of such self-motion illusions in VR was used as a starting point in order to study how self-motion simulation can eventually be improved in VR.

Spatial presence occupies an important role in this context, as we expected this to be an essential factor in enabling robust and effortless spatial orientation and task performance. Furthermore, according to our spatial orientation framework (von der Heyde and Riecke 2002; Riecke 2003), we propose that spatial presence is a necessary prerequisite for quick, robust, and effortless spatial orientation behaviour in general and for automatic spatial updating in particular. Thus, increasing spatial presence would in turn be expected to increase the overall convincingness and perceived realism of the simulation, thus bringing us one step closer to our ultimate goal of real world-like interaction with and navigation through the virtual environment. A first step towards this goal would be to show that increasing spatial presence in a VR simulation increases perception of illusory self-motion. This issue will be elaborated upon in more detail in Sect. 9.4.

9.1 Motivation and Background

Although virtual reality technology has been developing at an amazing pace during the last decades, existing virtual environments and simulations are still not able to evoke a compelling illusion of self-motion that occurs without any delay to the visual motion onset (Hettinger et al. 2014; Riecke 2011; Schulte-Pelkum 2007). Similarly, presence – i.e., the feeling of being and acting in the simulated virtual environment – is often limited or disrupted for users exposed to a VR simulation: Slater and Steed have introduced the concept of breaks in presence (BIP), which describes the frequent phenomenon that users suddenly become aware of the real environment and do not feel present in the VR simulation anymore (Slater and Steed 2000).

While the use of VR applications has widely spread in various fields, such as entertainment, training, research, and education, there are a number of problems that users are confronted with. In this section, we will highlight some of these problems that we see as crucial for the further use and promotion of VR technology.

9.1.1 Spatial Orientation Problems in VR

One important limitation of most VR setups stems from the observation that users get easily disoriented or lost while navigating through virtual environments (e.g., Chance et al. 1998; Ruddle 2013). Moreover, it is not yet fully understood where exactly these problems arise from. Several studies have shown that allowing for physical motions can increase spatial orientation ability, compared to situations where only visual information about the travelled path is available (Bakker et al. 1999; Chance et al. 1998; Klatzky et al. 1998; Riecke et al. 2010; Ruddle and Lessels 2006; Waller et al. 2004). Ruddle and Lessels demonstrated for example that allowing participants to physically walk around while wearing a head-mounted-display (HMD) dramatically improved performance for a navigational search task, whereas adding only physical rotation did not show any improvement (Ruddle and Lessels 2006). Other studies, however, showed that physical rotations are critical for basic spatial orientation tasks (Bakker et al. 1999; Chance et al. 1998; Riecke et al. 2010; see, however, Avraamides et al. 2004) but not sufficient for more complex tasks (Ruddle and Peruch 2004; Ruddle 2013). In apparent conflict to the above-mentioned studies, there are also several experiments that demonstrate that physical motions do not necessarily improve spatial orientation at all (Kearns et al. 2002; Riecke et al. 2002, 2005a; Waller et al. 2003). Highly naturalistic visual stimuli alone can even be sufficient for enabling good spatial orientation (Riecke et al. 2002) and/or automatic spatial updating (Riecke et al. 2005a, 2007) if they include useful landmarks, whereas simple optic flow typically seems insufficient (Bakker et al. 1999; Klatzky et al. 1998; Riecke et al. 2007; Riecke 2012). Especially when the visually displayed stimulus is sparse, display parameters such as the absolute size and field of view (FOV) of the displayed stimulus, but also the type of display itself (e.g., HMD vs. monitor vs. curved or flat projection screen) become critical factors (Bakker et al. 1999; Bakker et al. 2001; Klatzky et al. 1998; Riecke et al. 2005b; Tan et al. 2006).

We propose that spatial presence in the simulated scene might play an important – although often neglected – role in understanding the origins of the spatial orientation deficits typically observed in VR. In particular, the potential interference between the reference frames provided by the physical surroundings and the simulated virtual environment should be considered, as will be elaborated upon in Sect. 9.3.1 (see also Avraamides and Kelly 2008; May 1996, 2004; Riecke and McNamara submitted; Wang 2005).

9.1.2 Spatial Misperception in VR

Apart from the spatial orientation problems often observed in VR, there are also serious although well-known systematic misperceptions associated with many VR displays. Several studies showed for example that especially head-mounted displays (HMDs) often lead to systematic distortions of both perceived distances and turning angles (Bakker et al. 1999, 2001; Creem-Regehr et al. 2005; Grechkin et al. 2010; Riecke et al. 2005b; Tan et al. 2006). The amount of systematic misperception in VR is particularly striking in terms of perceived distance: While distance estimations using blindfolded walking to previously seen targets are typically rather accurate and without systematic errors for distances up to 20 m for targets in the real world (Loomis et al. 1992, 1996; Rieser et al. 1990; Thomson 1983), comparable experiments where the visual stimuli were presented in VR typically report compression of distances as well as a general underestimation of egocentric distances, especially if HMDs are used (Creem-Regehr et al. 2005; Grechkin et al. 2010; Thompson et al. 2004; Willemsen et al. 2008; Witmer and Sadowski 1998). Even a wide-FOV (140° × 90°) HMD-like Boom display resulted in a systematic underestimation of about 50 % for simulated distances between 10 and 110 ft (Witmer and Kline 1998). A similar overestimation and compression in response range for HMDs has also been observed for visually simulated rotations (Riecke et al. 2005b). So far, only projection setups with horizontal field of views of 180° or more could apparently enable close-to-veridical perception (Plumert et al. 2004; Riecke et al. 2002, 2005b; see, however, Grechkin et al. 2010), even though the FOV alone is not sufficient to explain the systematic misperception of distances in VR (Knapp and Loomis 2004). Hence, further research is required to compare and evaluate different display setups and simulation paradigms in terms of their effectiveness for both spatial presence and self-motion simulation.

9.1.3 The Challenge of Self-Motion Simulation

When we move through our environment, either by locomotion or transportation in a vehicle, virtually all of our senses are activated. The human senses that are considered as most essential for self-motion perception are the visual and vestibular modalities (Dichgans and Brandt 1978; Howard 1982). Most motion simulators are designed to provide stimulation for these two senses. The most common design for motion platforms is the Stewart Platform, which has six degrees of freedom and uses six hydraulic or electric actuators that are arranged in a space-efficient way to support the moving platform (Kemeny and Panerai 2003). Typically, a visualization setup is mounted on top of the motion platform, and users are presented with visual motion in a simulated environment while the platform mimics the corresponding physical accelerations. Due to technical limitations of the motion envelope, however, the motion platform cannot display exactly the same forces that would occur during the corresponding motion in the real world, but only mimic them using sophisticated motion cueing and washout algorithms that ideally move the simulator back to an equilibrium position at a rate below the motion human detection threshold (e.g., Berger et al. 2010; Conrad et al. 1973). To simulate a forward acceleration, for example, an initial forward motion of the platform is typically combined with tilting the motion platform backwards to mimic the feeling of being pressed into the seat and to simulate the change of gravito-inertial force vector.

Apart from being rather large and costly, the most common problem associated with current motion simulators is the frequent occurrence of severe motion sickness (Bles et al. 1998; Guedry et al. 1998; Kennedy et al. 2010; Lawson et al. 2002). As already mentioned, the technical limitation in self-motion simulation is imposed by the fact that most existing motion platforms have a rather limited motion range.

Consequently, they can only reproduce some aspects of the to-be-simulated motion veridically, and additional filtering is required to reduce the discrepancy between the intended motion and what the actual platform is able to simulate (e.g., Berger et al. 2010; Conrad et al. 1973). The tuning of these “washout filters” is a tedious business, and is typically done manually in a trial-and-error approach where experienced evaluators collaborate with washout filter experts who iteratively adjust the filter parameters until the evaluators are satisfied. While this manual approach might be feasible for some specific applications, a more general theory and understanding of the multi-modal simulation parameters and their relation to human self-motion perception is needed to overcome the limitations and problems associated with the manual approach. Such problems are evident for example in many flight and driving applications, where training in the simulator has been shown to cause misadapted behaviour that can be problematic in the corresponding real-world task (Boer et al. 2000; Burki-Cohen et al. 2003; Mulder et al. 2004). Attempts to formalize a comprehensive theory of motion perception and simulation in VR are, however, limited by our insufficient understanding of what exactly is needed to convey a convincing sensation of self-motion to users of virtual environments, and how this is related to the multi-modal sensory stimulation and washout filters in particular (Grant and Reid 1997; Stroosma et al. 2003; Telban and Cardullo 2001). Over the last decade, we investigated the possibility that not only the motion cueing algorithms and filter settings, but also high-level factors such as spatial presence might have an influence on the magnitude and believability of the perceived self-motion in a motion simulator. In order to increase spatial presence in the simulator, we provided realistic, consistent multi-modal stimulation to visual, auditory and tactile senses, and evaluated how vection and presence develop under different combinations of conditions (Riecke et al. 2005c, e; Riecke 2011; Schulte-Pelkum 2007).

Such above-mentioned shortcomings of most current VR setups limit the potential use of virtual environments for many applications. If virtual environments are to enable natural, real life-like behaviour that is indistinguishable from the real world or at least equally effective, then there is still a lot of work to be done, both in the fields of presence and self-motion simulation. VR technology is more and more turning into a standard tool for researchers who study self-motion perception, and many motion simulators use immersive setups such as head-mounted-displays (HMDs), wide-screen projection setups or 3D display arrays. It is thus important to systematically investigate potential influences of presence on self-motion perception and vice versa. It is possible that inconsistent findings in the recent self-motion perception literature might partly be attributable to uncontrolled influences of presence or other higher-level factors. Similarly, in presence research, the possibility that perceived self-motion in VR might have an effect on the extent to which one feels present in the simulated environment has received only little attention so far.

The following sections will provide brief literature overviews on self-motion illusions (“vection”) (Sect. 9.2) and some relevant aspects of the concept of presence (Sect. 9.3), followed by some theoretical considerations regarding how these two phenomena might be inter-related. In this context, we present and discuss in Sects. 9.4 and 9.5 results from two of our own experiments that demonstrate that not only low-level, bottom-up factors (as was often believed), but also higher cognitive contributions, top-down effects, and spatial presence in particular, can enhance self-motion perception and might thus be important factors that should receive more research attention. We finish the chapter by proposing an integrative theoretical framework that sketches how spatial presence and vection might be inter-related, and what consequences this implies in terms of applications and research questions (Sects. 9.6 and 9.7).

9.2 Literature Overview on the Perception of Illusory Self-Motion (Vection)

In this section,[1] we will provide a brief review of the literature on self-motion illusions that is relevant for the current context. More comprehensive reviews on visually induced vection are provided by, e.g., Andersen (1986), Dichgans and Brandt (1978), Howard (1982, 1986), Mergner and Becker (1990), Warren and Wertheim (1990). Vection with a specific focus on VR, motion simulation, and undesirable side-effects has more recently been reviewed in Hettinger et al. (2014), Lawson and Riecke (2014), Palmisano et al. (2011), Riecke and Schulte-Pelkum (2013), Riecke (2011), Schulte-Pelkum (2007).

When stationary observers view a moving visual stimulus that covers a large part of the FOV, they can experience a very compelling and embodied illusion of self-motion in the direction opposite to the visual motion. Many of us have experienced this illusion in real life: For example, when we are sitting in a stationary train and watch a train pulling out from the neighbouring track, we will often (erroneously) perceive that the train we are sitting in is starting to move instead of the train on the adjacent track (von Helmholtz 1866). This phenomenon of illusory self-motion has been termed “vection” and has been investigated for well over a century (von Helmholtz 1866; Mach 1875; Urbantschitsch 1897; Warren 1895; Wood 1895). Vection has been shown to occur for all motion directions and along all motion axes: Linear vection can occur for forward-backward, up-down, or sideways motion (Howard 1982). Circular vection can be induced for upright rotations around the vertical (yaw) axis, and similarly for the roll axis (frontal axis along the line of sight, like in a “tumbling room”), and also around the pitch axis (an imagined line passing through the body from left to right). The latter two forms of circular vection are especially nauseating, since they include a strong conflict between visual and gravitational cues and in particular affect the perceived vertical (Bles et al. 1998).

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[1] Sections 9.2, 9.6 and 9.7 of this chapter are, in part, based on (Riecke and Schulte-Pelkum 2013), with kind permission from Springer Science+Business Media: Riecke BE, Schulte-Pelkum J (2013) Perceptual and Cognitive Factors for Self-Motion Simulation in Virtual Environments: How Can Self-Motion Illusions (“Vection”) Be Utilized? In: Steinicke F, Visell Y, Campos J, Lécuyer A (eds) Human Walking in Virtual Environments. Springer, New York, pp 27–54, © Springer Science+Business Media New York 2013.

One of the most frequently investigated types of vection is circular vection around the earth-vertical axis. In this special situation where the observer perceives self-rotation around the earth-vertical axis, there is no interfering effect of gravity, since the body orientation always remains aligned with gravity during illusory self-rotation. In a typical classic circular vection experiment, participants are seated inside a rotating drum that is painted with black and white vertical stripes, a device called optokinetic drum. After the drum starts to rotate, the onset latency until the participant reports perceiving vection is measured. The strength of the illusion is measured either by the duration of the illusion, or by some indication of perceived speed or intensity of rotation, e.g., by magnitude estimation or by letting the participant press a button every time they think they have turned 90° (e.g., Becker et al. 2002).

In a similar manner, linear vection can be induced by presenting optic flow patterns that simulate translational motion. The traditional method used to induce linear vection in the laboratory is to use two monitors or screens facing each other, with the participant's head centred between the two monitors and aligned parallel to the screens, such that they cover a large part of the peripheral visual field (Berthoz et al. 1975; Johansson 1977; Lepecq et al. 1993). Optic flow presented in this peripheral field induces strong linear vection. For example, Johansson (1977) showed that observers perceive an “elevator illusion”, i.e., upward linear vection, when downward optic flow is shown. Other studies used monitors or projection screens in front of the participant to show expanding or contracting optic flow fields (Andersen and Braunstein 1985; Palmisano 1996). Comparing different motion directions shows greater vection facilitation for up-down (elevator) vection, presumably because visual motion does not suggest a change in the gravito-inertial vector as compared to front-back or left-right motion (Giannopulu and Lepecq 1998; Trutoiu et al. 2009).

In recent times, VR technology has been successfully introduced to perceptual research as a highly flexible research tool (Hettinger et al. 2014; Mohler et al. 2005; Nakamura and Shimojo 1999; Palmisano 1996, 2002; Riecke et al. 2005c). It has been shown that both linear and circular vection can be reliably induced using modern VR technology, and the fact that this technology allows for precise experimental stimulus control under natural or close-to-natural stimulus conditions is much appreciated by researchers (see reviews in Hettinger et al. 2014; Lawson and Riecke 2014; Palmisano et al. 2011; Riecke and Schulte-Pelkum 2013; Riecke 2011; Schulte-Pelkum 2007).

Before discussing possible inter-relations between presence and vection, let us first consider the most relevant findings from the literature on both vection (subsections below) and presence (Sect. 9.3). Traditionally, the occurrence of the self-motion illusion has been thought to depend mainly on bottom-up or low-level features of the visual stimulus. In the following, we will review some of the most important low-level parameters that have been found to influence vection (Sects. 9.2.1, 9.2.2, 9.2.3, 9.2.4, 9.2.5 and 9.2.6) and conclude this section with a discussion of possible higher-level or top-down influences on vection (Sect. 9.2.7).

9.2.1 *Size of the Visual FOV*

Using an optokinetic drum, Brandt and colleagues found that visual stimuli covering a large FOV induce stronger circular vection and result in shorter onset latencies than when smaller FOVs are used (Brandt et al. 1973). The strongest vection was observed when the entire FOV was stimulated. Limiting the FOV systematically increased onset latencies and reduced vection intensities. It was also found that a black and white striped pattern of 30° diameter that was viewed in the periphery of the visual field induces strong vection, at levels comparable to full field stimulation, whereas the identical 30° stimulus did not induce vection when it was viewed in the central FOV. This observation led to the conclusion of a "peripheral dominance" for illusory self-motion perception. Conversely, the central FOV was thought to be more important for the perception of object motion (as opposed to self-motion). However, this view was later challenged by Andersen and Braunstein (1985) and Howard and Heckmann (1989). Andersen and Braunstein showed that a centrally presented visual stimulus showing an expanding radial optic flow pattern that covered only 7.5° was sufficient to induce forward linear vection when viewed through an aperture. Howard and Heckmann (1989) proposed that the reason Brandt et al. (1973) found a peripheral dominance was likely due to a confound of misperceived foreground-background relations: When the moving stimulus is perceived to be in the foreground relative to a static background (e.g., the mask being used to cover parts of the FOV), it will not induce vection. They suspected that this might have happened to the participants in the Brandt et al. study, and they could confirm their hypothesis in their experiment by placing the moving visual stimulus either in front or in the back of the depth plane of the rotating drum. Their data showed that a central display would induce vection if it is perceived to be in the background. Thus, the original idea of peripheral dominance for self-motion perception should be reassessed. The general notion that larger FOVs are more effective for inducing vection, however, does hold true. In fact, when the perceived depth of the stimulus is controlled for, the perceived intensity of vection increases linearly with increasing stimulus size, independent of stimulus eccentricity (how far in the periphery the stimulus is presented) (Nakamura 2008). For virtual reality applications, this means that large-FOV displays are better suitable for inducing a compelling illusion of self-motion.

9.2.2 *Foreground-Background Separation Between a Stationary Foreground and a Moving Background*

As already briefly mentioned in the subsection above, a moving stimulus has to be perceived to be in the background in order to induce vection. A number of studies have investigated this effect (Howard and Heckmann 1989; Howard and Howard

1994; Nakamura 2006; Ohmi et al. 1987). All those studies found a consistent effect of the depth structure of the moving stimulus on vection: Only moving stimuli that are perceived to be in the background will reliably induce vection. If a stationary object is seen behind a moving stimulus, no vection will occur (Howard and Howard 1994). That is, the perceived foreground-background or figure-ground relationship can essentially determine the occurrence and strength of vection (Kitazaki and Sato 2003; Ohmi et al. 1987; Seno et al. 2009). Following the reasoning of Dichgans and Brandt, one could argue that the very occurrence of vection might be due to our inherent assumption of a stable environment (Dichgans and Brandt 1978) or a “rest frame” (Prothero and Parker 2003; Prothero 1998): When we see a large part of the visual scene move in a uniform manner, especially if it is at some distance away from us, it seems reasonable to assume that this is caused by ourselves moving in the environment, rather than the environment moving relative to us. The latter case occurs only in very rare cases in natural occasions, such as in the train illusion, where our brain is fooled to perceive self-motion. It has been shown that stationary objects in the foreground will increase vection if they partly occlude a moving background (Howard and Howard 1994), and that a foreground that moves slowly in the direction opposite to that of the background will also facilitate vection (Nakamura and Shimojo 1999). In Sect. 9.4, we will present some recent data that extend these findings to more natural stimuli and discuss implications for self-motion simulation from an applied perspective.

9.2.3 Spatial Frequency of the Moving Visual Pattern

Diener et al. (1976) observed that moving visual patterns that contained high spatial frequencies are perceived to move faster than similar visual patterns of lower spatial frequencies, even though both move at identical angular velocities. This means that a vertical grating pattern with, e.g., 20 contrasts (such as black and white stripes) per given visual angle will be perceived to move faster than a different pattern with only 10 contrasts within the same visual angle. Palmisano and Gillam (1998) revealed that there is an interaction between the spatial frequency of the presented optic flow and the retinal eccentricity: While high spatial frequencies produce most compelling vection in the central FOV, peripheral stimulation results in stronger vection if lower spatial frequencies are presented. This finding contradicts earlier notions of peripheral dominance (see Sect. 9.2.1) and shows that both high- and low spatial frequency information is involved in the perception of vection, and that mechanisms of self-motion perception differ depending on the retinal eccentricity of the stimulus. In the context of VR, this implies that fine detail included in the graphical scene may be more beneficial in the central FOV, while stimuli in the periphery might be rendered at lower resolution and fidelity, thus reducing overall simulation cost (see also discussion in Wolpert 1990).

9.2.4 Velocity and Direction of the Visual Stimulus

Howard and Brandt et al. reported that the intensity and perceived speed of self-rotation in circular vection around the yaw axis is linearly proportional to the velocity of the optokinetic stimulus up to values of approximately 90°/s (Brandt et al. 1973; Howard 1986). Note that the perceived velocity interacts with the spatial frequency of the stimulus, as detailed in Sect. 9.2.3. While Brandt et al. (1973) report that the vection onset latency for circular vection is more or less constant for optical velocities up to 90°/s, others report that very slow movement below the vestibular threshold results in earlier vection onset (Wertheim 1994). This apparent contradiction might, however, be due to methodological differences: While Brandt et al. accelerated the optokinetic drum in darkness up to a constant velocity and measured vection onset latency from the moment the light was switched on, the studies where faster vection onset was found for slow optical velocities typically used sinusoidal motion with the drum always visible.

Similar relations between stimulus velocity and vection have been observed for linear motion: Berthoz et al. (1975) found a more or less linear relationship between perceived self-motion velocity and stimulus velocity up to a certain level where an upper limit of the sensation of vection was reached. Interestingly, thresholds for backward and downward vection have been found to be lower than for forward and upward vection, respectively (Berthoz and Droulez 1982). The authors assumed that this result reflects normal human behaviour: While we perceive forward motion quite often and are thus well used to it, we are hardly exposed to linear backward motions, such that our sensitivity for them might be lower. In general, so-called elevator (up-down) vection is perceived earlier and as more compelling than other motion directions (Giannopulu and Lepecq 1998; Trutoiu et al. 2009). This might be related to up-down movements being aligned with the direction of gravity for upright observers, such that gravitational and acceleration directions are parallel. Interestingly, Kano found that onset latencies for vertical linear vection are significantly shorter than for forward and backward vection when observers are seated upright, but this difference disappeared when participants observed the identical stimuli in a supine position (Kano 1991). It is possible that this effect might be related to different utricular and macular sensitivities of the vestibular system, but it is yet unclear how retinal and gravitational reference frames interact during vection.

Although vection is generally enhanced when the visuo-vestibular conflict is reduced, e.g., in patients whose vestibular sensitivity is largely reduced, such as bilaterally labyrinth defective participants (Cheung et al. 1989; Johnson et al. 1999), Palmisano and colleagues showed convincingly that adding viewpoint jitter to a vection-in-depth visual stimulus consistently enhances vection, even though it should enhance the sensory conflict between visual and vestibular cues (Palmisano et al. 2000, 2011).

9.2.5 *Eye Movements*

It has long been recognized that eye movements influence the vection illusion. Mach (1875) was the first to report that vection will develop faster if observers fixate a stationary target instead of letting their eyes follow the stimulus motion. This finding has been replicated many times (e.g., Becker et al. 2002; Brandt et al. 1973). Becker et al. investigated this effect in an optokinetic drum by systematically varying the instructions how to “watch” the stimulus: In one condition, participants had to follow the stimulus with their eyes, thus not suppressing the optokinetic nystagmus (OKN, which is the reflexive eye movement that also occurs in natural situations, e.g., when one looks out of the window while riding a bus). In other conditions, participants either had to voluntarily suppress the OKN by fixating a stationary target that was presented on top of the moving stimulus, or they were asked to stare through the moving stimulus. Results showed that vection developed faster with the eyes fixating a stationary fixation point as compared to participants staring through the stimulus. Vection took longest to develop when the eyes moved naturally, following the stimulus motion. Besides fixating and staring, looking peripherally or shifting one’s gaze between central and peripheral regions can also improve forward linear vection (Palmisano and Kim 2009).

9.2.6 *Non-visual Cues and Multimodal Consistency*

Most of the earlier vection literature has been concerned with visually induced vection. Vection induced by other sensory modalities, such as moving acoustic stimuli, has therefore received little attention, even though auditorily induced circular vection and nystagmus have been reported as early as 1923 (Dodge 1923) and since been replicated by several researchers (Hennebert 1960; Lackner 1977; Marme-Karelse and Bles 1977), see also reviews in Riecke et al. (2009b) and Väljamäe (2009). Lackner (1977) demonstrated, for example, that a rotating sound field generated by an array of loudspeakers could induce vection in blindfolded participants. More recent studies demonstrated that auditory vection can also be induced by headphone-based auralization using generic head-related transfer functions (HRTFs), both for rotations and translations (Larsson et al. 2004; Riecke et al. 2005e, 2009b; Väljamäe et al. 2004; Väljamäe 2009). Several factors were found to enhance auditory vection (see also reviews in Riecke et al. 2009b; Väljamäe 2009): For example, both the realism of the acoustic simulation and the number of sound sources were found to enhance vection. It is important to keep in mind, however, that auditory vection occurs only in about 25–70 % of participants and is far less compelling than visually induced vection, which can be indistinguishable from actual motion (Brandt et al. 1973). Hence, auditory cues alone are not sufficient to reliably induce a compelling self-motion sensation. However, adding consistent spatialized auditory cues to a naturalistic visual stimulus can enhance both vection and overall presence in the simulated environment, compared to non-spatialized sound or no sound (Keshavarz et al. 2013; Riecke et al. 2005d, 2009b). Similarly, moving sound fields can enhance "biomechanical" vection induced by stationary participants stepping along a rotating floor platter (Riecke et al. 2011). This suggests that multi-modal consistency might be beneficial for the effectiveness of self-motion simulations.

This notion is supported by Wong and Frost, who showed that circular vection is facilitated when participants are provided with an initial physical rotation ("jerk") that accompanies the visual motion onset (Wong and Frost 1981). Even though the physical motion did not match the visual motion quantitatively, the qualitatively correct physical motion signal accompanying the visual motion supposedly reduced the visuo-vestibular cue conflict, thus facilitating vection.

Similar vection-facilitating effects have more recently been reported for linear vection when small linear forward jerks of only a few centimetres accompanied the onset of a visually displayed linear forward motion in VR. This has been shown for both passive movements of the observer (Berger et al. 2010; Riecke et al. 2006b; Riecke 2011; Schulte-Pelkum 2007) and for active, self-initiated motion cueing using a modified manual wheelchair (Riecke 2006) or a modified Gyroxus gaming chair where participants controlled the virtual locomotion by leaning into the intended motion direction (Feuereissen 2013; Riecke and Feuereissen 2012). For passive motions, combining vibrations and small physical movements (jerks) together was more effective in enhancing vection than either vibrations or jerks alone (Schulte-Pelkum 2007, exp. 6).

Helmholtz suggested already in 1866 that vibrations and jerks that naturally accompany self-motions play an important role for self-motion illusions, in that we expect to experience at least some vibrations or jitter (von Helmholtz 1866). Vibrations can nowadays easily be included in VR simulations and are frequently used in many applications. Adding subtle vibrations to the floor or seat in VR simulations has indeed been shown to enhance not only visually-induced vection (Riecke et al. 2005c; Schulte-Pelkum 2007), but also biomechanically-induced vection (Riecke et al. 2009a) and auditory vection (Riecke et al. 2009a; Väljamäe et al. 2006; Väljamäe 2007), especially if accompanied by a matching simulated engine sound (Väljamäe et al. 2006, 2009). These studies provide scientific support for the usefulness of including vibrations to enhance the effectiveness of motion simulations – which is already common practice in many motion simulation applications. It remains, however, an open question whether the vection-facilitating effect of adding vibrations originates from low-level, bottom-up factors (e.g., by decreasing the reliability of the vestibular and tactile signals indicating "no motion") or whether the effect is mediated by higher-level and top-down factors (e.g., the vibrations increasing the overall believability and naturalism of the simulated motion), or both.

As both vibrations and minimal motion cueing can be added to existing VR simulations with relatively little effort and cost, their vection-facilitating effect is promising for many VR applications. Moreover, these relatively simple means of providing vibrations or jerks were shown to be effective despite being physically incorrect – while jerks normally need to be in the right direction to be effective and be synchronized with the visual motion onset, their magnitude seems to be of lesser importance. Indeed, for many applications there seems to be a surprisingly large coherence zone in which visuo-vestibular cue conflicts are either not noticed or at the least seem to have little detrimental effect (van der Steen 1998). Surprisingly, physical motion cues can enhance visually-induced vection even when they do not match the direction or phase of the visually-displayed motion (Wright 2009): When participants watched sinusoidal linear horizontal (left-right) oscillations on a head-mounted display, they reported more compelling vection and larger motion amplitudes when they were synchronously moved (oscillated) in the vertical (up-down) and thus orthogonal direction. Similar enhancement of perceived vection and motion amplitude was observed when both the visual and physical motions were in the vertical direction, even though visual and physical motions were always in *opposite* directions and thus out of phase by 180° (e.g., the highest visually depicted view coincided with the lowest point of their physical vertical oscillatory motion). In fact, the compellingness and amplitude of the perceived self-motion was not significantly smaller than in a previous study where visual and inertial motion was synchronized and not phase-shifted (Wright et al. 2005). Moreover, for both horizontal and vertical visual motions, perceived motion directions were almost completely dominated by the visual, not the inertial motion. That is, while there was some sort of "visual capture" of the perceived motion direction, the extent and convincingness of the perceived self-motion was modulated by the amount of inertial acceleration.

In two recent studies, Ash et al. showed that vection is enhanced if participants' active head movements are updated in the visual self-motion display, compared to a condition where the identical previously recorded visual stimulus was replayed while observers did not make any active head-movements (Ash et al. 2011a, b). This means that vection was improved by consistent multisensory stimulation where sensory information from own head-movements (vestibular and proprioceptive) matched visual self-motion information on the VR display (Ash et al. 2011b). In a second study with similar setup, Ash et al. (2011a) found that adding a deliberate display lag between the head and display motion modestly impaired vection. This finding is highly important since in most VR applications, end-to-end system lag is present, especially in cases of interactive, multisensory, real-time VR simulations. Despite technical advancement, it is to be expected that this limitation cannot be easily overcome in the near future.

Seno and colleagues demonstrated that air flow provided by a fan positioned in front of observers' face significantly enhanced visually induced forward linear vection (Seno et al. 2011b). Backward linear vection was not facilitated, however, suggesting that the air flow needs to at least qualitatively match the direction of simulated self-motion, similar to head wind.

Although multi-modal consistency in general seems to enhance vection, there seems to be at least one exception: while biomechanical cues from walking on a circular treadmill can elicit vection by themselves in blindfolded participants (Bles 1981; Bles and Kapteyn 1977) and also enhance visually induced vection (Riecke et al. 2009b; Väljamäe 2009) as well as biomechanically induced circular vection

(Riecke et al. 2011), linear treadmill walking can neither by itself reliably induce vection, nor does it reliably enhance visually-induced vection, as discussed in detail in Ash et al. (2013) and Riecke and Schulte-Pelkum (2013).

It remains puzzling how adding velocity-matched treadmill walking to a visual motion simulation can impair vection (Ash et al. 2012; Kitazaki et al. 2010; Onimaru et al. 2010) while active head motions and simulated viewpoint jitter clearly enhance vection (Palmisano et al. 2011). More research is needed to better understand under what conditions locomotion cues facilitate or impair linear vection, and what role the artificiality of treadmill walking might play. Nevertheless, the observation that self-motion perception can, at least under some circumstances, be impaired if visual and biomechanical motion cues are matched seems paradoxical (as it corresponds to natural eyes-open walking) and awaits further investigation. These results do, however, suggest that adding a walking interface to a VR simulator might potentially (at least in some cases) *decrease* instead of increase the sensation of self-motion and thus potentially decrease the overall effectiveness of the motion simulation. Thus, caution should be taken when adding walking interfaces, and each situation should be carefully tested and evaluated as one apparently cannot assume that walking will always improve the user experience and simulation effectiveness.

Note that there are also considerable differences between different people's susceptibility to vection and different vection-inducing stimuli, so it can be difficult to predict a specific person's response to a given situation. Palmisano and colleagues made recent progress towards that challenge, though, and showed that the strength of linear forward vection could be predicted by analysing participants' postural sway patterns without visual cues (Palmisano et al. 2014), which is promising.

In conclusion, there can often be substantial benefits in providing coherent self-motion cues in multiple modalities, even if they can only be matched qualitatively. Budget permitting, allowing for actual physical walking or full-scale motion or motion cueing on 6 degrees of freedom (DoF) motion platforms is clearly desirable and might be necessary for specific commercial applications like flight or driving simulation. When budget, space, or personnel is more limited, however, substantial improvements can already be gained by relatively moderate and affordable efforts, especially if consistent multi-modal stimulation and higher-level influences are thoughtfully integrated. Although they do not provide physically accurate simulation, simple means such as including vibrations, jerks, spatialized audio, or providing a perceptual-cognitive framework of movability can go a long way (Lawson and Riecke 2014; Riecke and Schulte-Pelkum 2013; Riecke 2009, 2011). Even affordable, commercially available motion seats or gaming seats can provide considerable benefits to self-motion perception and overall simulation effectiveness (Riecke and Feuereissen 2012).

As we will discuss in our conceptual framework in Sect. 9.6 in more detail, it is essential to align and tailor the simulation effort with the overarching goal: e.g., is the ultimate goal physical correctness, perceptual effectiveness, or behavioural realism? Or is there a stronger value put on user's overall enjoyment, engagement, and immersion, as in the case of many entertainment applications, which represent a considerable and increasing market share?

9.2.7 Cognitive, Attentional, and Higher-Level Influences on Vection

The previous subsections summarized research demonstrating a clear effect of perceptual (low-level) factors and bottom-up processes on illusory self-motion perception. In the remainder of this section, we would like to point out several studies which provide converging evidence that not only low-level factors, but also cognitive, higher-level processes as well as attention might play an important role in the perception of illusory self-motion, especially in a VR context (see also reviews in Riecke and Schulte-Pelkum (2013) and Riecke (2009, 2011)). That is, we will argue that vection can also be affected by what is outside of the moving stimulus itself, for example by the way we move and look at a moving stimulus, our pre-conceptions, intentions, and how we perceive and interpret the stimuli, which is of particular importance in the context of VR.

As mentioned in Sect. 9.2.2, it has already been proposed in 1978 that the occurrence of vection might be linked to our inherent assumption of a stable environment (Dichgans and Brandt 1978). Perhaps this is why the *perceived* background of a vection-inducing stimulus is typically the dominant determinant of the presence of vection and modulator of the strength of vection, even if the background is not physically further away than the perceived foreground (Howard and Heckmann 1989; Ito and Shibata 2005; Kitazaki and Sato 2003; Nakamura 2008; Ohmi et al. 1987; Seno et al. 2009). This "object and background hypothesis for vection" has been elaborated upon and confirmed in an elegant set of experiments using perceptually bistable displays like the Rubin's vase that can be perceived either as a vase or two faces (Seno et al. 2009). In daily life, the more distant elements comprising the background of visual scenes are generally stationary and therefore any retinal movement of those distant elements is more likely to be interpreted as a result of self-motion (Nakamura and Shimojo 1999). In VR simulations, these findings could be used to systematically reduce or enhance illusory self-motions depending on the overall simulation goal, e.g., by modifying the availability of real or simulated foreground objects (e.g., dashboards), changing peripheral visibility of the surrounding room (e.g., by controlling lighting conditions), or changing tasks/instructions (e.g., instructions to pay attention to instruments which are typically stationary and in the foreground).

In the study by Andersen and Braunstein described in Sect. 9.2.2, the authors remark that pilot experiments had shown that in order to perceive any self-motion, participants had to believe that they could actually be moved in the direction of perceived vection (Andersen and Braunstein 1985). Accordingly, participants were asked to stand in a movable booth and looked out of a window to view the optic flow pattern. Similarly, in a study by Lackner who showed that circular vection can be induced in blindfolded participants by a rotating sound field, participants were seated on a chair that could be rotated (Lackner 1977). Note that by making participants believe that they could, in fact, be moved physically, Andersen and Braunstein were able to elicit vection with a visual FOV as small as 7.5°, and Lackner (1977) and Larsson et al. (2004) were able to induce vection simply by presenting a moving sound field to blindfolded listeners. Under these conditions of limited or weak sensory stimulation, cognitive factors seem to become a relevant factor. It is possible that cognitive factors generally have an effect on vection, but that this has not been recognized so far due to a variety of reasons. For example, the cognitive manipulations might not have been powerful enough, or sensory stimulation might have been so strong that ceiling level was already reached, which is likely to be the case in an optokinetic drum that covers the full visible FOV.

In this context, a study by Lepecq and colleagues is of particular importance, as it explicitly addressed cognitive influences on linear vection (Lepecq et al. 1995): They found that 7 year old children perceive vection earlier when they are previously shown that the chair they are seated on can physically move in the direction of simulated motion – even though this never happened during the actual experiment. Interestingly, this vection-facilitating influence of pre-knowledge was not present in 11 year old children.

Prior knowledge of whether or not physical motions are possible do show some effect on adults as well: In a circular vection study in VR, 2/3 of the participants were fooled into believing that they physically moved when they were previously shown that the whole experimental setup can indeed be moved physically (Riecke et al. 2005e; Riecke 2011; Schulte-Pelkum 2007). Note, however, that neither vection onset times, nor vection intensity or convincingness were significantly affected by the cognitive manipulation. In another study, Palmisano and Chan (2004) demonstrated that cognitive priming can also affect the time course of vection: Adult participants experienced vection earlier when they were seated on a potentially movable chair and were primed towards paying attention to self-motion sensation, compared to a condition where they were seated on a stationary chair and instructed to attend to object motion, not self-motion.

Providing such a cognitive-perceptual framework of movability has recently been shown to also enhance auditory vection (Riecke et al. 2009a). When blindfolded participants were seated on a hammock chair while listening to binaural recordings of rotating sound fields, auditory circular vection was facilitated when participants' feet were suspended by a chair-attached footrest as compared to being positioned on solid ground. This supports the common practice of seating participants on potentially moveable platforms or chairs in order to elicit auditory vection (Lackner 1977; Väljamäe 2007, 2009).

There seems to be mixed evidence about the potential effects of attention and cognitive load on vection. Whereas Trutoiu et al. (2008) observed vection facilitation when participants had to perform a cognitively demanding secondary task, vection inhibition was reported by Seno et al. (2011a). When observers in Kitazaki and Sato (2003) were asked to specifically pay attention to one of two simultaneously presented upward and downward optic flow fields of different colours, the non-attended flow field was found to determine vection direction. This might, however, also be explained by attention modulating the perceived depth-ordering and foreground-background relationship, as discussed in detail in Seno et al. (2009). Thus, while attention and cognitive load can clearly affect self-motion illusions, further research is needed to elucidate underlying factors and explain seemingly conflicting findings. A recent study suggests that vection can even be induced when participants are not consciously aware of any global display motion, which was cleverly masked by strong local moving contrasts (Seno et al. 2012).

Studies on auditorily induces circular vection also showed cognitive or top-down influences: sound sources that are normally associated with stationary objects (so-called "acoustic landmarks" like church bells) proved more potent in inducing circular vection in blindfolded participants than artificial sounds (e.g., pink noise) or sound typically generating from moving objects (e.g., driving vehicles or foot steps) (Larsson et al. 2004; Riecke et al. 2005e).

A similar mediation of vection via higher-level mechanisms was observed when a globally consistent visual stimulus of a natural scene was compared to an upside-down version of the same stimulus (Riecke et al. 2005e, 2006a). Even though the inversion of the stimulus left the physical stimulus characteristics (i.e., the image statistics and thus bottom-up factors) essentially unaltered, both participants' rated presence in the simulated environment and the rated convincingness of the illusory self-motion were significantly reduced. This strongly suggests a higher-level or top-down contribution to presence and the convincingness of self-motion illusions. We posit that the natural, ecologically more plausible upright stimulus might have more easily been accepted as a stable "scene", which in turn facilitated both presence and the convincingness of vection. The importance of a naturalistic visual stimulus is corroborated by a study from Wright et al. (2005) that demonstrated that visual motion of a photo-realistic visual scene can dominate even conflicting inertial motion cues in the perception of self-motion.

Already 20 years ago, Wann and Rushton (1994) stressed the importance of an ecological context and a naturalistic optic array for studying self-motion perception. Traditional vection research has, however, used abstract stimuli like black and white striped patterns or random dot displays, and only recently have more naturalistic stimuli become more common in self-motion research (Mohler et al. 2005; Riecke et al. 2005c, 2006a; van der Steen and Brockhoff 2000). One might expect that more natural looking stimuli have the potential of not only inducing stronger vection, but also higher presence. Consequently, it seems appropriate to consider possible interactions between presence and vection.

Even though presence is typically not assessed or discussed in vection studies, it is conceivable that presence might nevertheless have influenced some of those results: For example, Palmisano (1996) found that forward linear vection induced by a simple random dot optic flow pattern was increased if stereoscopic information was provided, compared to non-stereoscopic displays. Even though presence was not measured in this experiment, it is generally known that stereoscopic displays increase presence (Freeman et al. 2000; IJsselsteijn et al. 2001). In another study, van der Steen and Brockhoff (2000) found unusually short vection onset latencies, both for forward linear and circular yaw vection. They used an immersive VR setup consisting of a realistic cockpit replica of an aircraft on a motion simulator with a wide panoramic projection screen. Visual displays showed highly realistic scenes of landscapes as would be seen from an airplane. Even though presence was not assessed here, it is possible that the presumably high level of presence might have contributed to the strong vection responses of the observers.

In conclusion, cognitive factors seem to become more relevant when stimuli are ambiguous or have only weak vection-inducing power, as in the case of auditory vection (Riecke et al. 2009a) or sparse or small-FOV visual stimuli (Andersen and Braunstein 1985). It is conceivable that cognitive factors generally have an effect on vection, but that this has not been widely recognized for methodological reasons. For example, the cognitive manipulations might not have been powerful enough or free of confounds, or sensory stimulation might have been so strong that ceiling level was already reached, which is likely the case in an optokinetic drum that completely covers the participant's field of vision.

9.3 A Selective Review on Presence

"Presence" denotes the phenomenon that users who are experiencing a simulated world in VR can get a very compelling illusion of being and acting in the simulated environment instead of the real environment, a state also described as "being there" or "spatial presence" (Hartmann et al. 2014). Several different definitions for presence have been suggested in the literature, and comprehensive reviews of different conceptualizations, definitions, and measurement methods are provided in the current book and, e.g., Biocca (1997), IJsselsteijn (2004), Lee (2004), Loomis (1992), Nash et al. (2000), Sadowski and Stanney (2002), Schultze (2010), Steuer (1992).

The fact that presence does occur, even though current VR technology can afford only relatively sparse and insufficient sensory stimulation, is remarkable by itself. Even with the most sophisticated current immersive VR technology, a simulated environment will never be seriously mistaken as reality by any user, even if one's attention might be primarily drawn to the virtual environment. So, what is presence, and what is its relevance for the use of current VR systems?

One central problem associated with the concept of presence is its rather diffuse definition, which evokes theoretical and methodological problems. In order to theoretically distinguish presence from other related concepts, the term "immersion" is often used to clarify that presence (and in particular "spatial presence") is about the sensation of being at another place than where one's own body is physically located, while immersion usually refers to a psychological process of being completely absorbed in a certain physical or mental activity (e.g., reading a book or playing a game), such that one loses track of time and of the outside world (Jennett et al. 2008; Wallis and Tichon 2013). Note that we distinguish here between "immersion" as the psychological process and "immersiveness" as the medium's ability to afford the psychological process of immersion (Vidyarthi 2012), which is and extension of what Slater (1999) referred to as "system immersion". "Immersive VR", then, describes VR systems that have the technical prerequisites and propensities (e.g., high perceptual realism and fidelity) to create an immersive experience in the user. It has been pointed out that presence and immersion or involvement are logically distinct phenomena, even though they seem to be empirically related (Haans and IJsselsteijn 2012). A captivating narrative or content in VR might draw off attention from sensorimotor mismatches due to poor simulation fidelity, such as a noticeable delay of a visual scene that is experienced using a head-tracked HMD. On the other hand, a low-tech device such as a book can be highly immersive, depending on its form and content. It is commonly assumed that highly immersive VR systems can also create a high sense of presence, but the relation between the concepts still remains unclear, and attempts to capture these phenomena in one comprehensive theoretical framework are rare (Haans and IJsselsteijn 2012; Vidyarthi 2012).

The most frequently used measurement methods of presence rely on post-exposure self-report questionnaires like the Presence Questionnaire (PQ) by Witmer et al. (2005), or the IGroup Presence Questionnaire (IPQ) by Schubert et al. (2001). Here, VR users are asked to report from memory the intensity of presence they perceived in the preceding VR-scene. Factor analytic surveys suggest that such questionnaires seem to be able to reliably identify different aspects of presence, and a number of questionnaires have gained a significant level of acceptance in the community, with reliability measures of Cronbach's α at .85 for the IPQ, for example. However, some authors have questioned the validity of self-report measures of presence, and suggested physiological measures, such as heart-rate, skin conductance or event-evoked cortical responses etc. as more objective alternatives that allow for real-time measurement of presence (Slater and Garau 2007; Slater 2004). The idea is that a high level of perceived presence of a user in a simulated environment should be associated with similar physiological reactions as in the real world. Following this logic, Meehan et al. observed systematic changes in a number of physiological responses when users approached a simulated virtual pit that induced fear, which correlated with reported levels of presence (Meehan et al. 2002). Freeman et al. (2000) used postural responses to visual scenes of a driving simulator as a measure of presence. Postural responses to visual scenes depicting accelerations, braking, taking a curve etc. from the perspective of a rally car driver were stronger in conditions with stereoscopic visual stimulation in which reported presence was higher.

While such approaches might potentially help circumventing some of the problems associated with subjective report measures of presence, their utility remains unclear so far. Recently, the fMRI paradigm has been adopted in presence research, and some neural correlates of presence have been observed (Bouchard et al. 2012; Hoffman et al. 2003). However, this endeavor is only at its beginning yet, and this method will be practicable only to a limited number of research labs, at least for the near future.

Finally, another approach in this field is the use of behavioral measures (Bailenson et al. 2004; Wallis and Tichon 2013). If users could intuitively behave in a virtual environment in a natural manner and perform tasks as well as in reality, such as wayfinding, controlling a vehicle in a simulation etc., one central goal in VR research might be considered as fulfilled. Behavioural measures have the advantage that they can be recorded unobtrusively, in an ongoing perception-action-loop. Differential analyses of behavioural outcomes and their relation to presence have the potential to reveal new insights to this field. Along this line, a recent study about simulator-based training efficacy showed that reported presence levels of trainees in a train simulator correlated moderately with overall training efficacy after 1 year, but was not sensitive to performance differences in three different simulator types used in the study. In contrast, a perceptual judgment task about speed perception was able to predict different training efficacy of the three types of simulators (Wallis and Tichon 2013).

What becomes apparent from the considerations so far is that depending on the purpose and context of the VR simulation, be it training, entertainment, research, education etc., the relevance of presence and other concepts might vary, and there might be interactions. We will argue that a pragmatic, behaviorally oriented approach appears promising for the near future.

For the purpose of our study, the definition by Witmer and Singer which states that "…presence is defined as the subjective experience of being in one place or environment, even when one is physically situated in another" (Witmer and Singer 1998) describes well the relevant aspects of spatial presence in the context of self-motion simulation in VR, as we will outline in the following.

9.3.1 Presence and Reference Frames

One important aspect VR simulations we would like to point out here is that in any VR application, the user is always confronted with two, possibly competing, egocentric representations or reference frames: On the one hand, there is the real environment (i.e., the physical room where the VR setup is situated). On the other hand, there is the computer-generated VE, which provides an intended reference frame or representation that might interfere with the real world reference frame unless they present the same environment in perfect spatio-temporal alignment. Riecke and von der Heyde proposed that the degree to which users accept the VE as their primary reference frame might be directly related to the degree of spatial presence experience in the VE (von der Heyde and Riecke 2002; Riecke 2003). In their framework, the consistency or lack of interference between the VR and real world reference frame is hypothesized to be a necessary prerequisite for enabling compelling spatial presence. Conversely, any interference between conflicting egocentric reference frames is expected to decrease spatial presence and thereby also automatic spatial updating and natural, robust spatial orientation in the VE (Riecke et al. 2007; Riecke 2003). This notion of conflicting reference frames is closely related to the sensorimotor interference hypothesis proposed by May and Wang, which attributes the difficulty of imagined perspective switches (at least in part) to processing costs resulting from an interference between the sensorimotor and the to-be-imagined perspective (May 1996, 2004; Wang 2005; see also discussion in Avraamides and Kelly 2008; Riecke and McNamara submitted).

This emphasizes the importance of reducing users' awareness of the physical surroundings, which has already been recognized by many researchers and VR designers. If not successful, a perceived conflict between competing egocentric reference frames arises which can critically disrupt presence, i.e., the feeling of being and acting in the virtual environment (IJsselsteijn 2004; Slater and Steed 2000), see also Hartmann et al.'s chapter in this volume (Hartmann et al. 2014).

9.3.2 Resence and Self-Motion Perception

In the following, we will review a selection of papers that investigated presence in the context of self-motion perception. Slater and colleagues found a significant positive association between extent and amount of body movement and subjective presence in virtual environments (Slater et al. 1998). Participants experienced a VE through a head-tracked HMD, and depending on task condition, one group was required to move their head and body a lot, while the other group could do the task without much body movement. The group that had to move more showed much higher presence ratings in the post-experimental presence questionnaires. It is plausible that the more an observer wearing an HMD experiences perceptual consequences of his or her own body movements in the simulated environment, the more he or she will experience presence in the simulated VE and not in the real world.

There are several studies that investigated the influence of stereoscopic presentation on presence and vection: Freeman, IJsselsteijn and colleagues observed that presence and postural responses were increased when observers watched a stereoscopic movie that was shot from the windshield of a rally car, as compared to a monoscopic version of the film (Freeman et al. 2000; IJsselsteijn et al. 2001). Vection, however, was not improved by the stereoscopic presentation. Note that in the studies by Freeman et al. and IJsselsteijn et al., presence was assessed with only one post-test question: Participants were simply asked to rate how much they felt present in the displayed scene as if they were "really there". Participants were to place a mark in the scale depicting a continuum between the extremes "not at all there" and "completely there" on a line connecting the two points.

Since presence is conceptualized as a multi-dimensional construct, it is possible that assessing presence with only one item was too course to reveal a correlation with vection. This motivated us to perform a more fine-grained analysis on possible relations between presence and vection using the IPQ presence questionnaire (see Sect. 9.4.5).

9.3.3 Conclusions

In the preceding two subsections, we reviewed the relevant literature on vection and presence, and extracted a number of observations that indicate that attentional, cognitive, and higher-level factors might affect the occurrence and strength of vection. Since VR is increasingly being used as a standard tool in vection research, it seems worthwhile to investigate possible connections between presence and vection, be they correlational or causal. Previous studies that failed to show such a connection have the limitation that presence was assessed only coarsely (Freeman et al. 2000; IJsselsteijn et al. 2001). Furthermore, a number of studies measured vection but not presence, even though factors that are known to influence presence (such as stereoscopic viewing) were manipulated (Palmisano 1996). Given these circumstances, we aimed to perform a more detailed investigation of the potential relations between presence and vection. We were guided by the hypothesis that the different dimensions, which in sum constitute presence, might have differential influences on different aspects of the self-motion illusion. We decided to measure presence using the IPQ presence questionnaire by Schubert et al. (2001), and to assess vection by measuring vection onset latency, vection intensity, and the convincingness of illusory self-motion. Correlation analyses between the IPQ presence scales and the three vection measures are the core of the analysis.

9.4 Experiments Investigating the Relations Between Spatial Presence, Scene Consistency and Self-Motion Perception

In the following, we will briefly present the results of two of our own studies that directly addressed the potential relations between presence, naturalism of the stimulus, reference frames, and self-motion perception. A detailed description of the experiments can be found in Riecke et al. (2006a) (Experiment 1) and Riecke et al. (2004) (Experiment 2). Based on the above-mentioned idea that vection depends on the assumption of a stable environment, we expected that the sensation of vection should be enhanced if the presented visual stimulus (e.g., a virtual environment) is more easily “accepted” as a real world-like stable reference frame. That is, we predicted that vection in a simulated environment should be enhanced if participants feel spatially present in that environment and might thus more readily expect the virtual environment to be stable, just like the real world is expected to be stable.

Presence has been conceptualized as a multi-dimensional construct, and is usually measured with questionnaires where users are asked to provide subjective ratings about the degree to which they felt present in the VR environment after exposure, as discussed above (IJsselsteijn 2004; Nash et al. 2000; Sadowski and Stanney 2002; Schultze 2010). Despite being aware of problems associated with this introspective measurement method, we decided to use the Igroup Presence Questionnaire (IPQ) by Schubert et al. (2001) for our current study, which allowed us to test specific hypotheses about relations between different constituents of presence and vection. Using factor analyses, Schubert et al. extracted three factors that constitute presence based on a sample of 246 participants. These three factors were interpreted as *spatial presence* – the relation between one’s body and the VE as a space; *involvement* – the amount of attention devoted to the VE; and *realness* – the extent to which the VE is accepted as reality. The results of our own correlation analyses between vection in VR and the IPQ presence scores will be presented later in Sect. 9.4.5.

The goal of the first study presented here in more detail (henceforth named Experiment 1)[2] was to determine whether vection can be modulated by the nature of the vection-inducing visual stimulus, in particular whether or not it depicts a natural scene that allows for the occurrence of presence or not. On the one hand, the existence of such higher-level contributions would be of considerable theoretical interest, as it challenges the prevailing opinion that the self-motion illusion is mediated solely by the physical stimulus parameters, irrespective of any higher cognitive contributions. On the other hand, it would be important for increasing the effectiveness and convincingness of self-motion simulations: Physically moving the observer on a motion platform is rather costly, labour-intensive, and requires a large laboratory setup and safety measures. Thus, if higher-level and top-down mechanisms could help to improve the simulation from a perceptual level and in terms of effectiveness for the given task, this would be quite beneficial, especially because these factors can often be manipulated with relatively simple and cost-effective means, especially compared to using full-fledged motion simulators. The second study to be presented (subsequently referred to as Experiment 2) is an extension to the first study and investigated effects of minor modifications of the projection screen (Riecke et al. 2004; Riecke and Schulte-Pelkum 2006).

9.4.1 Methods

In the following, we will present the main results of Experiment 1 & 2 together with a novel reanalysis and discussion of possible causal relations between presence and self-motion perception. In both experiments, participants were seated in front of a curved projection screen (45° × 54° FOV) and were asked to rate circular vection induced by rotating visual stimuli that depicted either a photorealistic roundshot of a natural scene (the Tübingen market place, see Fig. 9.1, top) or scrambled (globally inconsistent) versions thereof that were created by either slicing the original roundshot horizontally and randomly reassembling it (Fig. 9.1, condition b) or by scrambling image parts in a mosaic-like manner (Fig. 9.1, condition B).

9.4.2 Hypotheses

Scene scrambling was expected to disrupt the global consistency of the scene and pictorial depth cues contained therein. We expected that this should impair the believability of the stimuli and in particular spatial presence in the simulated scene. All of these factors can be categorized as cognitive or higher-level contributions

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[2] This section presents a re-analysis of the most relevant experimental conditions from Riecke et al. (2006a) (experiment 1) and is in part based on that paper, with an additional discussion in the context of presence and experiment 2 and the framework presented in this chapter.

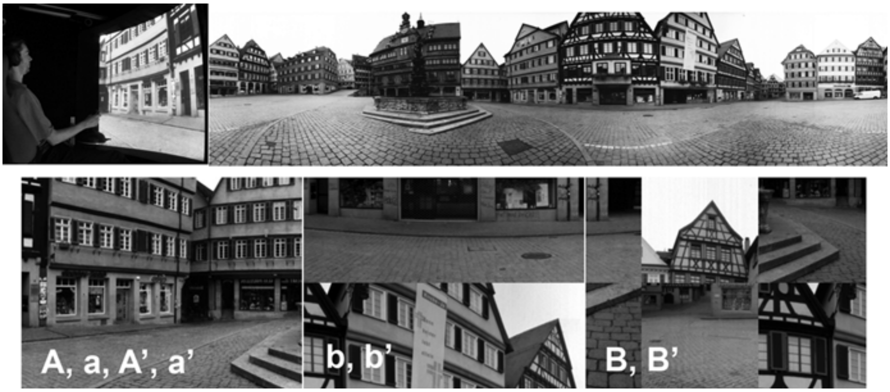

Fig. 9.1 Setup and subset of the stimuli used in Experiment 1 and 2 (Riecke et al. 2004, 2006a). *Top left*: Participant seated in front of curved projection screen displaying a view of the Tübingen market place. *Top right*: 360° roundshot of the Tübingen Market Place. *Bottom*: 54°×45° view of three of the stimuli discussed here. *Left*: Original, globally consistent image (*a, A, a', A'*), *Middle*: 2 slices per 45° FOV (*b, b'*), and *Right*: 2×2 mosaics per 45°×45° FOV (*B*, *B'*). Note that the original stimuli were presented in colour

(Riecke et al. 2005e; Riecke 2009, 2011). Note, however, that scene scrambling had only minor effects on bottom-up factors (physical stimulus properties) like the image statistics. Thus, any effect of global scene consistency on vection should accordingly be attributed to cognitive, top-down effects, and might be mediated by spatial presence in the simulated scene.

The original experiment followed a 2 (session: mosaic, slices)×4 (scrambling severity: intact, 2, 8, 32 mosaics/slices per 45° FOV)×2 (rotation velocity: 20°/s, 40°/s)×2 (turning direction) within-subject factorial design with two repetitions per condition. In terms of our current purpose of discussing the relation between presence and vection, the comparison between the globally consistent and the most moderate scrambling level (2 slices/mosaics per 45° FOV) is the most critical, and we will constrain our discussion to those conditions (i.e., we omit the 8 & 32 slices/mosaics condition and the 40°/s conditions, which are discussed in detail in Riecke et al. 2006a). Presence was measured for each visual stimulus using the 14-item Igroup Presence Questionnaire (IPQ, Schubert et al. 2001) after the vection experiments.

9.4.3 Results and Discussion

As indicated in Figs. 9.3 and 9.4, global scene consistency played the dominant role in facilitating vection and presence, and any global inconsistency reduced vection as well as spatial presence and involvement consistently. As discussed in detail in (Riecke et al. 2006a), this result cannot be convincingly explained on the basis of bottom-up factors alone, as the physical stimulus parameters and images statistics were hardly affected by the scene scrambling. In fact, the mosaic-like scrambling (condition B) introduced additional vertical high-contrast edges and thus higher spatial frequencies – both of which are bottom-up factors that would, if anything, be expected to *enhance* the perceived stimulus speed (Distler 2003) and vection (Dichgans and Brandt 1978). Nevertheless, vection ratings were identical to the horizontally sliced stimuli (condition b) that lacked these additional high-contrast vertical edges. Together, these results support the notion that cognitive and top-down factors like the global consistency of the pictorial depth and scene layout might have caused the increased self-motion sensation, and that spatial presence and involvement (which were arguably directly manipulated by the scene scrambling) might have mediated this effect.

9.4.4 Experiment 2 – Unobtrusive Modifications of a Projection Screen Can Facilitate Both Vection and Presence

Results from Experiment 1 suggest that spatial presence might have mediated the increase in vection observed for the globally consistent stimuli. It is, however, also feasible that vection might conversely be able to mediate an increase in spatial presence. In fact, Experiment 2 seems to suggest just that (Riecke et al. 2004; Riecke and Schulte-Pelkum 2006): The experimental stimuli and procedures were identical to Experiment 1 described above, apart from the fact that subtle marks (scratches) were added to the periphery of the projection screen (upper left corner, as illustrated in Fig. 9.2). Ten new participants were used in this study. The motivation for this experiment stemmed from pilot experiments that revealed a strong, unexpected vection-enhancing effect when the screen was accidentally scratched.

As can be seen in Figs. 9.3 and 9.4, Experiment 2 showed a similar benefit of the globally consistent stimulus for both vection and presence. The comparison between the clean screen (Exp. 1) and marked screen (Exp. 2), however, showed a considerable and highly significant vection-facilitating effect of the subtle marks on the screen for all dependent measures (see Fig. 9.3 and Table 9.1). The marks reduced vection onset time by more than a factor of two, and vection intensity and convincingness ratings were raised to almost ceiling level. Moreover, even spatial presence and involvement were unexpectedly increased by a significant amount. Note that the marks enhanced presence and vection even though only 10 % (i.e., 1 out of 10) of the participants were able to report that they had noticed these marks in a post-experimental interview.

Note that different participant populations were used for Experiment 1 and 2, and systematic differences in the participant populations might have contributed to the observed facilitating effect of the marks on the screen. Nevertheless, given that the results proved highly significant (see Table 9.1), and the magnitude of the effect was relatively large (see Figs. 9.3 and 9.4), this suggests that the observed facilitation of vection and presence by the added marks is unlikely to be merely an artefact.

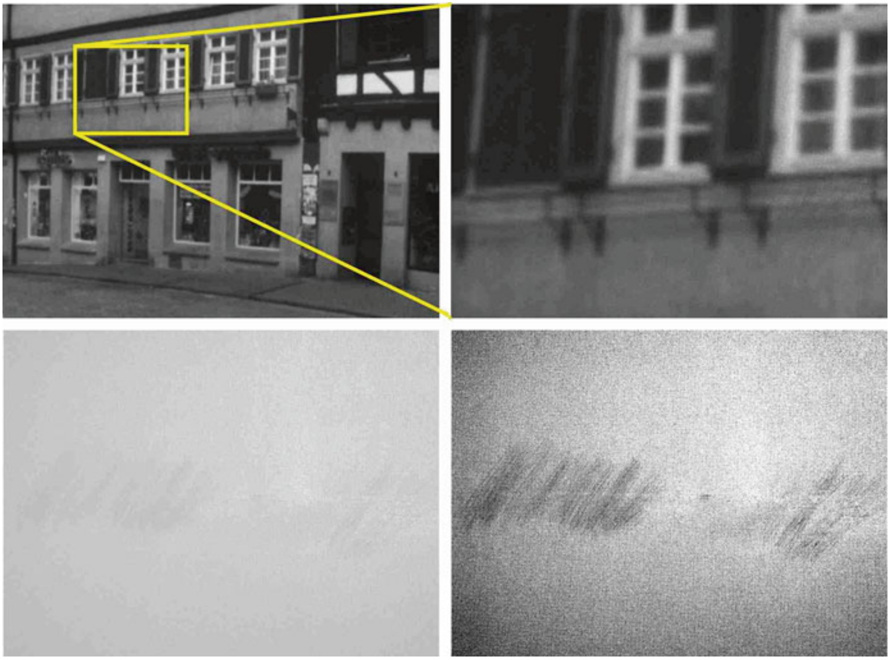

Fig. 9.2 *Top left*: View of the projection screen displaying the market scene. The marks are located at the upper-left part of the screen, as illustrated by the close-ups to the right and below. *Bottom*: Close-up of the same region as above (right), but illuminated with plain white light to illustrate the marks. *Left*: The original photograph demonstrating the unobtrusive nature of the marks (diagonal scratches). *Right*: Contrast-enhanced version of the same image to illustrate the marks (Image reprinted from Riecke et al. (2004, 2005c) with permission)

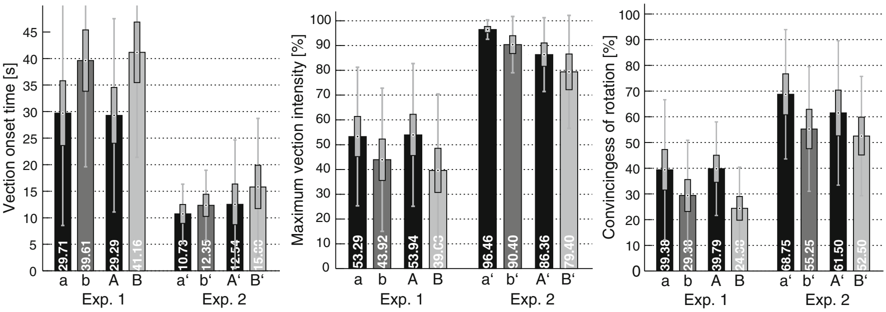

Fig. 9.3 Mean of the three vection measures for the clean screen (Experiment 1) and the marked screen (Experiment 2), each plotted for the globally consistent stimuli (*a*, *A*, *a'*, *A'*) and the sliced (*b*, *b'*) and scrambled (*B*, *B'*) stimuli. Boxes and whiskers depict one standard error of the mean and one standard deviation, respectively. Note the strong vection-facilitating effect of the additional marks on the screen (Exp. 2) for all measures

Fig. 9.4 Mean presence ratings for the clean screen (Experiment 1) and the marked screen (Experiment 2), each plotted for the globally consistent stimuli (*a, A, a', A'*) and the sliced (*b, b'*) and scrambled (*B, B'*) stimuli. Note also the consistently higher presence ratings for globally consistent stimuli and the marked screen

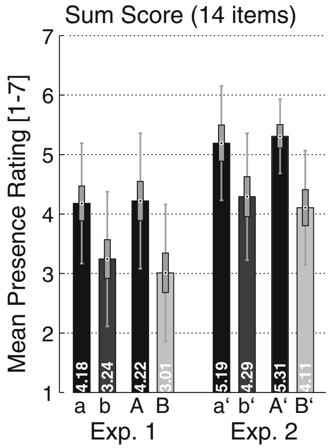

Table 9.1 ANOVA table for Experiment 1 & 2

	Vection onset time		Convincingness of vection		Vection intensity		Presence sum score	
	F(1,20)	p	F(1,20)	p	F(1,20)	p	F(1,20)	p
Globally consistent vs. inconsistent	6.63	.018*	24.8	<.0005***	12.3	.002**	41.7	<.0005***
Horizontally slices vs. mosaic-like scrambled	0.562	.46	0.797	.38	2.07	.17	0.159	.7
Clean vs. marked projection screen	13.8	.001**	9.38	.006**	21.3	<.0005***	9.13	.007**

*p < .05, **p < .01, ***p < .001

Table of ANOVA results for all four dependent variables of Experiment 1 & 2. The natural, intact scene (“globally consistent”) induces higher vection and presence, and no difference is found between the two degraded stimuli (sliced vs. scrambled). For the screen with the marks (Experiment 2), all vection and presence ratings are higher than in Experiment 1 with the clean screen. Note that the first two factors are within-subject factors, whereas the third factor is a between-subject factor

9.4.5 Correlations Between Presence Factors and Vection Measures

To investigate the structure and constituting elements of presence, a factor analysis was performed for the IPQ presence questionnaire data of Experiments 1 & 2. First, separate analyses were performed for both experiments. Subsequently, data from both experiments were pooled, since the patterns of results were very similar.

In all three analyses, a two-dimensional structure of presence was revealed: Factor 1 contained items about realism of the simulated scene and spatial presence (e.g., sense of being in the virtual environment), while factor 2 contained items that addressed attentional aspects or involvement (e.g., awareness of real surroundings of the simulator vs. the simulated environment). It is noteworthy that presence in the current study showed a structure similar to the one observed in Schubert and co-workers' original study (Schubert et al. 2001), even though the current study used only 22 participants, and there was not really much interactivity involved in our experiments: As soon as participants pressed a button, the visual scene started to rotate, and after a fixed time, the motion stopped automatically. Apart from that, there was no perceivable consequence of any of the participants' actions. One small difference between the Schubert et al. (2001) and the current study is that for the latter, realism and spatial presence were subsumed in one factor (named "spatial presence" here for convenience) and not in two separate factors.

In order to investigate how the different aspects of presence related to different aspects of self-motion perception, separate correlation analyses were performed between factor 1 (interpreted as "spatial presence") and factor 2 ("involvement") of the presence questionnaire and the three vection measures onset time, intensity, and convincingness for Experiment 1 & 2. The resulting paired-samples correlations (r) and the corresponding p-values are summarized in Table 9.2.

To ensure higher statistical power and better interpretability of the correlations, the data of the 22 participants of two experiments were in addition pooled, and the same analyses were performed as before (see Table 9.2, bottom row). This is a valid method since the stimuli and procedures were exactly identical; the only difference was the presence or absence of subtle marks on the projection screens. The results for the pooled data are qualitatively similar to the two separate analyses, but they show a clearer pattern now, as was expected from the larger sample size:

While the online measures of vection onset time (and to some degree also vection intensity) were more closely related to the involvement/attention aspect of overall presence (factor 2, as assessed using the IPQ), the subjective convincingness ratings that followed each trial were more tightly related to the spatial presence

Table 9.2 Correlations between vection and presence measures

		Factor 1 (spatial presence)			Factor 2 (involvement)		
		Vection onset time	Convincingness of vection	Vection intensity	Vection onset time	Convincingness of vection	Vection intensity
Experiment 1 (N = 12)	r	.041	**.579***	−.229	**−.620***	.307	.469
	p	.90	**.049**	.474	**.031**	.332	.124
Experiment 2 (N = 10)	r	.015	.479	**.673***	.629	.306	.535
	p	.970	.192	**.049**	.070	.424	.138
Exp. 1 & 2 pooled (N = 22)	r	−.259	**.630***	.232	**−.710****	**.473***	**.616****
	p	.257	**.002**	.311	**<.001**	**.030**	**.003**

*p < .05, **p < .01, ***p < .001

Bold numbers indicate significant effects (p < .05)

Paired-samples correlations for Experiment 1, Experiment 2, and the pooled data from Experiments 1 & 2. Correlations were computed between all three vection measures (vection onset time, convincingness, and vection intensity) and the factor values of the two presence factors aspects of overall presence (factor 1). It should be pointed out that given the small sample size (N = 10, 12, or 22 (pooled data)), these correlations are quite substantial. This asymmetry between spatial presence and attention/involvement should be taken into consideration when attempting to improve VR simulations. Depending on task requirements, different aspects of presence might be relevant and should receive more attention or simulation effort – we will elaborate on this topic below.

9.5 Discussion: A Direct Link Between Presence and Vection?

In the previous section, we presented results from two experiments that suggest that not only low-level, but also higher-level factors such as spatial presence and the interpretation of the stimulus might have an influence on vection. Notably, different dimensions of presence correlated differentially with different aspects of vection: While spatial presence seems to be closely related to the convincingness of the rotation illusion, involvement and attentional aspects in the simulation were more closely related to the onset time and intensity of the illusion. Previous studies that failed to reveal such connections had used only rather coarse methods (Freeman et al. 2000; IJsselsteijn et al. 2001). In the following, we will discuss how low-level as well as higher-level effects might have contributed to produce these results.

9.5.1 Low-Level vs. Higher-Level Influences in Experiment 1 & 2

In past vection research, self-motion illusions were typically induced using abstract stimuli like black and white geometric patterns. Here, we showed that the illusion can be enhanced if a natural scene is used instead: Experiment 1 & 2 revealed that a visual stimulus depicting a natural, globally consistent scene can produce faster, stronger, and more convincing sensation of illusory self-motion than more abstract, sliced or scrambled versions of the same stimulus. There are a number of possible low-level and high-level mechanisms that might have contributed to this effect, as we will discuss in more detail below. Figure 9.5 provides a schematic overview of these different proposed influences and underling mechanisms.

9.5.1.1 Number of Vertical High-Contrast Edges

There are at least two bottom-up factors that would predict an increase in vection for the mosaic-like scrambled stimuli, compared to the intact and sliced stimuli. First, adding vertical high-contrast edges is known to enhance vection (Dichgans and

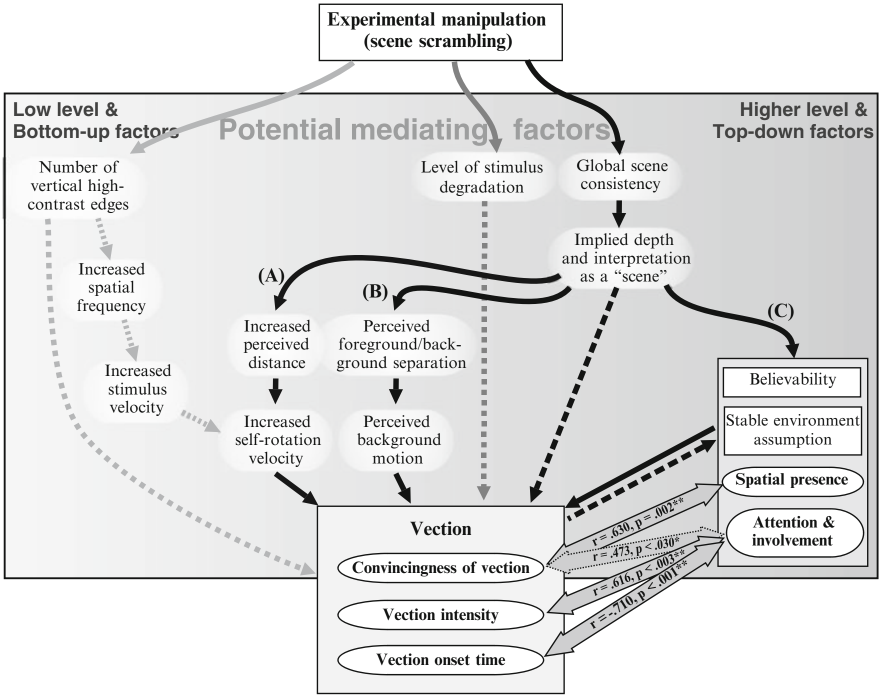

Fig. 9.5 Schematic illustration of the different mechanisms and mediating factors that might have contributed to the systematic effect of scene scrambling on vection and presence in Experiment 1 & 2 (Riecke et al. 2004, 2006a). These hypothesized mechanisms range from lower-level and bottom-up factors (*left side* of figure) to more cognitive and higher-level factors (*right*). *Solid black arrows* indicate pathways that are most likely and consistent with the current data, whereas *dashed and dotted arrows* indicate pathways that are less and least probable/supported by the current data, respectively. Presence and vection measures are depicted as *oval framed boxes*, and the *grey double-sided connecting arrows* depict significant correlations between presence and vection measures. Results from the scene scrambling in both experiments suggest that vection might at least in part be mediated by higher-level and/or top-down mechanism like pictorial depth cues, global scene consistency, or presence. The factor "level of stimulus degradation" was not presented in the current analysis in this chapter, see Riecke et al. (2006a) for a more detailed discussion (Figure adapted from Riecke et al. (2006a))

Brandt 1978). Second, these additional high-contrast vertical edges increase the contrast and spatial frequency of a moving stimulus, which has been shown to result in higher perceived stimulus velocities (Distler 2003). As higher rotational velocities induce vection more easily than slower velocities for the current setup and stimuli (Riecke et al. 2006a; Schulte-Pelkum et al. 2003), one would predict that the mosaics should improve vection as compared to the horizontal slices or intact stimulus. The results of Experiment 1 & 2 showed, however, no such vection-facilitating effect of the additional vertical edges at all. Instead, adding the vertical high contrast edges actually *reduced* vection, compared to the intact stimulus. This is illustrated by the left pathway in Fig. 9.5. This suggests that the data cannot be convincingly explained by low-level, bottom-up processes alone, and that the bottom-up contributions (more vertical contrast edges in the mosaic-like scrambled stimulus) were dominated by cognitive and top-down processes (consistent reference frame for the intact market scene). This is corroborated by the fact that the additional vertical contrast edges in the mosaic-like scrambled stimulus did not increase vection compared to the horizontally sliced stimulus (which did not have any more vertical contrast edges than the intact stimulus).

In the following, we will discuss three possible cognitive or higher-level mechanisms that might have contributed to the vection-enhancing effect of the globally consistent stimulus. These different mechanisms are visualized in Fig. 9.5 as different pathways labelled (A), (B), and (C). Note, however, that the current studies were not designed to disambiguate between those different mechanisms, and future experiments would be needed to tackle this issue.

9.5.1.2 Pathway (A): Increase in Perceived Depth and Perceived Self-Motion Velocity

Wist and colleagues demonstrated that the perceived velocity of circular vection (which is often used as a measure of vection intensity) depends not only on the angular velocity of the stimulus as one might expect, but also on the perceived distance of the stimulus (Wist et al. 1975). In a carefully designed study, they systematically manipulated the perceived distance of the vection-inducing stimulus using different methodologies (Pulfrich effect or accommodative and fusional convergence), and observed a linear increase of perceived self-motion velocity with increasing perceived distance.

Even though none of these depth cues were employed in the current experiment, the unscrambled stimulus contained an abundance of globally consistent pictorial depth cues (e.g., relative and absolute size, occlusion, texture gradients, and linear perspective) that might have increased its perceived distance. The scrambled stimuli, however, contained hardly any consistent pictorial depth cues and were thus more likely to be perceived as a 2D-surface at the distance of the projection screen. In fact, some participants mentioned in post-experimental interviews that the scrambled stimuli looked a bit like flat wallpaper. Thus, one might argue that the pictorial depth cues present in the globally consistent stimulus might have been sufficient to increase the perceived distance and thus indirectly increase perceived vection velocity – which is in turn associated with enhanced vection for the stimuli in Experiment 1 & 2 (Riecke et al. 2004, 2006a). This hypothesis is illustrated as pathway (A) in Fig. 9.5. Further studies that explicitly measure vection, perceived distance, and perceived velocity would be required, though, to test this hypothesis.

9.5.1.3 Pathway (B): Perceived Foreground-Background Separation and Perceived Background Motion

As discussed in Sect. 9.2.2 above, not only absolute perceived distance of the vection-inducing stimulus, but also the perceived foreground-background separation can affect vection: When the vection-inducing stimulus consists of several parts (superimposed or spatially separated), vection seems to be dominated by the one that is *perceived* to be further away – even in cases when it is, in fact, physically closer (Howard and Heckmann 1989; Ohmi et al. 1987; Seno et al. 2009).

This opens up another possibility about how scene scrambling might have affected vection: The globally consistent scene structure and depth cues of the intact stimulus might have resulted in a *perceived* foreground-background separation between the projection screen and surrounding setup (both being perceived as foreground) and the projected globally consistent stimulus (being perceived as further away and thus as a background). Consequently, the globally consistent stimulus motion might have been perceived as background motion and thus indirectly facilitated vection, even though there was no physical depth separation between the projection screen and the moving visual stimulus (cf. pathway (B) in Fig. 9.5). Hence, presentation of a natural, globally consistent scene that contains an abundance of pictorial depth cues might be sufficient to yield a perceived foreground-background capable of enhancing illusory self-motion perception. This would have interesting implications both for our basic understanding of self-motion perception and for self-motion simulation applications (see also discussion in Riecke and Schulte-Pelkum 2013; Seno et al. 2009).

9.5.1.4 Pathway (C): Presence and the Assumption of a Stable Reference Frame

Results from the presence questionnaires show that the natural, globally consistent scene was not only associated with enhanced vection, but also with higher presence ratings than any of the sliced or scrambled stimuli. Together with the consistent correlations between vection and presence ratings, this raises the possibility that presence and vection might be directly linked. That is, we propose that the globally consistent, naturalistic scene might have afforded (i.e., implied the possibility of) movement through the scene and allowed for higher believability and presence in the simulated environment. Thus, the natural scene could have provided observers with a more convincing, stable reference frame with respect to which motions are being judged more easily as self-motions instead of object or image motions. The proposed mediating influence of presence for the self-motion illusion is in agreement with the "presence hypothesis" proposed by Prothero, which states that "the sense of presence in the environment reflects the degree to which that environment influences the selected rest frame" (Prothero 1998). This is illustrated as pathway (C) in Fig. 9.5. Even though this study showed a clear correlation between vection and presence, further research is needed to determine if there is actually a *causal* relation between presence and vection. Most importantly, the discussion of Experiments 1 & 2 in Sect. 9.5.1 suggests that higher-level, top-down factors do, in fact, play a considerable role in self-motion perception and thus deserve more attention both in motion simulation applications and in fundamental research, where they have received only little attention until recently – see, however, noteworthy exceptions mentioned in Sect. 9.2.7 and Riecke (2009, 2011).

9.5.2 Origin of Vection- and Presence-Enhancing Effect of Adding Marks to the Projection Screen

When comparing Experiment 1 and Experiment 2, both vection and presence clearly benefited from using a projection screen that contained additional minor marks (scratches) in the periphery, but was otherwise of the identical size, material, and reflection properties. Note that this effect occurred consistently across all dependent measures. So how might this rather surprising effect be explained?

It is known from the vection literature that the visually induced self-motion illusion can be enhanced rather easily by asking participants to fixate on a stationary object while observing the moving stimulus (Becker et al. 2002; Brandt et al. 1973). This effect can be further increased if the visual stimulus is perceived as being stationary *in front* of a moving background stimulus (Howard and Heckmann 1989; Nakamura and Shimojo 1999), whereas stationary objects that appear to be *behind* the moving objects tend to impair vection (Howard and Howard 1994). Note that observers in these studies were asked to explicitly fixate and focus on those targets. The observed vection-facilitating effect of a static fixation has been attributed to an increased relative motion on the retina. The novel finding from the comparison of Experiment 1 and 2 is that a similar effect can also occur even if the stationary objects (or marks) are not fixated and are hardly noticeable – only one participant was, in fact, able to report having noticed the marks. Note that observers in our study were instructed to view the stimulus in a normal and relaxed manner, without trying to suppress the optokinetic reflex (OKR) by, e.g., staring through the screen or fixating on a static point. Furthermore, there was no physical foreground-background separation between the static marks on the screen and the moving scene (Nakamura and Shimojo 1999). Hence, these low-level factors cannot account for the observed vection-enhancing effect.

Nevertheless, the vection-facilitating effect of the marks was quite obvious and the effect size was comparable to that of an explicit fixation point in traditional studies using full-field stimulation in an optokinetic drum: Becker et al. reported for example a decrease of vection onset latencies from 30s without fixation to 10s with fixation at a rotational velocity of 30°/s (Becker et al. 2002).

From the current data, we can only speculate about the underlying processes that could explain the vection-enhancing effect of the marks in our study. We propose

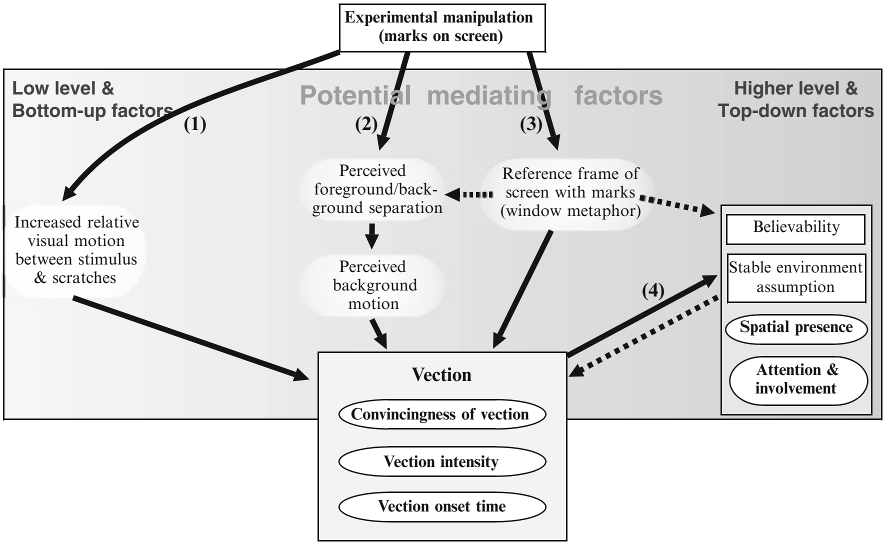

Fig. 9.6 Schematic representation of the proposed mechanisms about how the experimental manipulation of adding marks to the screen might have affected vection and presence. *Solid black arrows* indicate pathways that seem likely and are consistent with the current data, whereas *dotted arrows* indicate more tentative lines of logic. The comparison of the two experiments suggests that the experimental manipulation of adding marks to the screen (*top* of the graph) might have indirectly affected spatial presence and involvement, in the sense that the enhancement of vection might have mediated or indirectly caused the observed increase in spatial presence. The marks are proposed to have facilitated vection via three potential pathways, labelled (*1*) – (*3*): First, they increased the relative visual motion between the moving stimulus and the stationary marks; Second, the marks might have fostered a perceptual foreground/background separation, such that the moving stimulus is more likely to interpreted as background motion, which is known to facilitate vection; Third, the marks might have provided a stable reference frame with respect to which visual motion might be more easily interpreted as self-motion than stimulus motion

three mechanisms that might have contributed (see Fig. 9.6, pathways (1) – (3)): First, adding the marks increased the relative visual motion between the moving stimulus and the stationary screen and marks, which might have facilitated vection as illustrated in pathway (1). Second, even though there was no physical depth separation whatsoever between the marks on the screen and the visual motion stimulus presented on the same screen, there might have been a perceptual foreground-background separation that might have facilitated vection, as depicted in pathway (2). That is, participants might somehow have attributed the marks to the foreground, similar to stains on a cockpit window, and the projected stimuli as moving with respect to that cockpit in the background, much like in an actual vehicle. The pictorial depth cues present in the intact or mildly scrambled stimuli might have supported this percept, as the displayed scene suggested a distance of several meters from the observer. This perceived background motion might have facilitated vection (Howard and Heckmann 1989; Nakamura and Shimojo 1999; Seno et al. 2009).

Third, the marks might have provided some kind of subtle stationary reference frame with respect to which the moving stimulus is being perceived (pathway (3)). A related study by Lowther and Ware demonstrated a similar vection-facilitating effect when using a stable foreground stimulus (Lowther and Ware 1996). Instead of using a subtle modification as in the current study, however, Lowther and Ware overlaid a clearly visible rectangular 5×5 grid onto a large flat projection screen that was used to present the moving stimuli in a VR setup. Nevertheless, the marks in the current study that were hardly noticed showed a vection-facilitating effect that was even stronger than for Lowther and Ware's clearly visible grid that extended over the whole screen. Obviously, further investigations are required to test the proposed explanation that the marks on the screen might provide some kind of subtle foreground reference frame that influences self-motion perception. If our hypothesis were true, it would have important implications for the design of convincing self-motion simulators, especially if participants would not have to be aware of the manipulation.

For most applications, it is neither desired nor feasible to restrict users' eye and head movements unnaturally. Hence, the current study could be exploited for self-motion simulations by including for example dirt or stains onto the real or simulated windshield of a vehicle cockpit – a minor, ecologically plausible manipulation that might also increase the perceived realism of the simulation. The current data would predict that such a simple measure might increase the convincingness and strength of self-motion perception without imposing unnatural constraints on the user's behaviour. The effect could probably be further enhanced by including stereoscopic depth cues that support the foreground/background separation between the cockpit/windshield and the outside scene (Howard and Heckmann 1989; Lowther and Ware 1996; Nakamura and Shimojo 1999; Seno et al. 2009).

In addition to the vection-facilitating effects, the minor scratches on the screen also clearly enhanced presence, which we had not at all predicted. In fact, we are not aware of any theoretical reason why simply adding scratches to the screen should *directly* increase presence or involvement in the simulation. Instead, one might expect a presence decline because of the degradation of the simulation fidelity due to the scratches. Nevertheless, adding the marks to the screen did significantly increase spatial presence and even involvement. Furthermore, observers who experienced stronger vection with the scratches on the screen reported also significantly higher presence. We posit that this effect might be attributed to the dynamical component of the visual stimulus, in the sense that the increase in the self-motion illusion might have indirectly caused or mediated the increase in presence and involvement. This hypothesis is illustrated in Fig. 9.6, pathway (4). If this were true, it would mean that an increased sensation of vection might also increase presence in VR. In fact, a similar finding was reported by Slater et al. (1998): As already mentioned in Sect. 9.3.2, they had found that observers who moved more in the VE reported higher presence. In the current study, however, observers experienced *passive* self-motion, similar to traveling in a vehicle and not self-generated motion by locomotion.

9.6 Conclusions and Conceptual Framework

In conclusion, the current experiments and the above literature review support the notion that cognitive or top-down mechanisms like spatial presence, the cognitive-perceptual framework of movability, as well as the interpretation of a stimulus as stable and/or belonging to the perceptual background, do all affect self-motion illusions, a phenomenon that was traditionally believed to be mainly bottom-up driven, as discussed in detail in Riecke and Schulte-Pelkum (2013). Riecke (2009, 2011), and Schulte-Pelkum (2007). This adds to the small but growing body of literature that suggests cognitive or top-down contributions to vection, as discussed in Sect. 9.2.7. Furthermore, the comparison of Experiment 1 and 2 suggests that presence might also be mediated by the amount of perceived self-motion in the simulated scene. Thus, it appears as if vection and presence might be able to mutually affect or support each other. While still speculative, this would be important not only for our theoretical understanding of self-motion perception, presence, and other higher-level phenomena, but also from an applied perspective of affordable yet effective self-motion simulation. In the following, we would like to broaden our perspective by trying to embed the current hypotheses and results into a more comprehensive tentative framework. This conceptual framework is sketched in Fig. 9.7 and will be elaborated upon in more detail below. It is meant not as a "true" theoretical model but as a tentative framework to support discussion and reasoning about these concepts and their potential interrelations.

Any application of VR, be it more research-oriented or application-oriented, is typically driven by a more or less clearly defined goal. In our framework, this is conceptualized as the "***effectiveness concerning a specific goal or application***" (Fig. 9.7, bottom box). Possible examples include the effectiveness of a specific pilot training program in VR, which includes how well knowledge obtained in the simulator transfers to corresponding real world situations, or the degree to which a given VR hardware and software can be used as an effective research tool that provides ecologically valid stimulation of the different senses.

So how can a given goal be approached and the goal/application-specific effectiveness be better understood and increased? There are typically a large number of potential contributing factors, which span the whole range from perceptual to cognitive aspects (see Fig. 9.7, top box). Potentially contributing factors include straightforward technical factors like the FOV and update rate of a given VR setup (which are typically low-level, bottom-up factors), the quality of the sensory stimulation with respect to the different individual modalities and their cross-modal consistency (which may have both a low- and higher-level component), and task-specific factors like the cognitive load or the users' instructions (which are often higher-level, top-down and thus more cognitive factors).

All of these factors might have an effect on both our perception and our action/behaviour in the VE. Here, we propose a framework where the different factors are

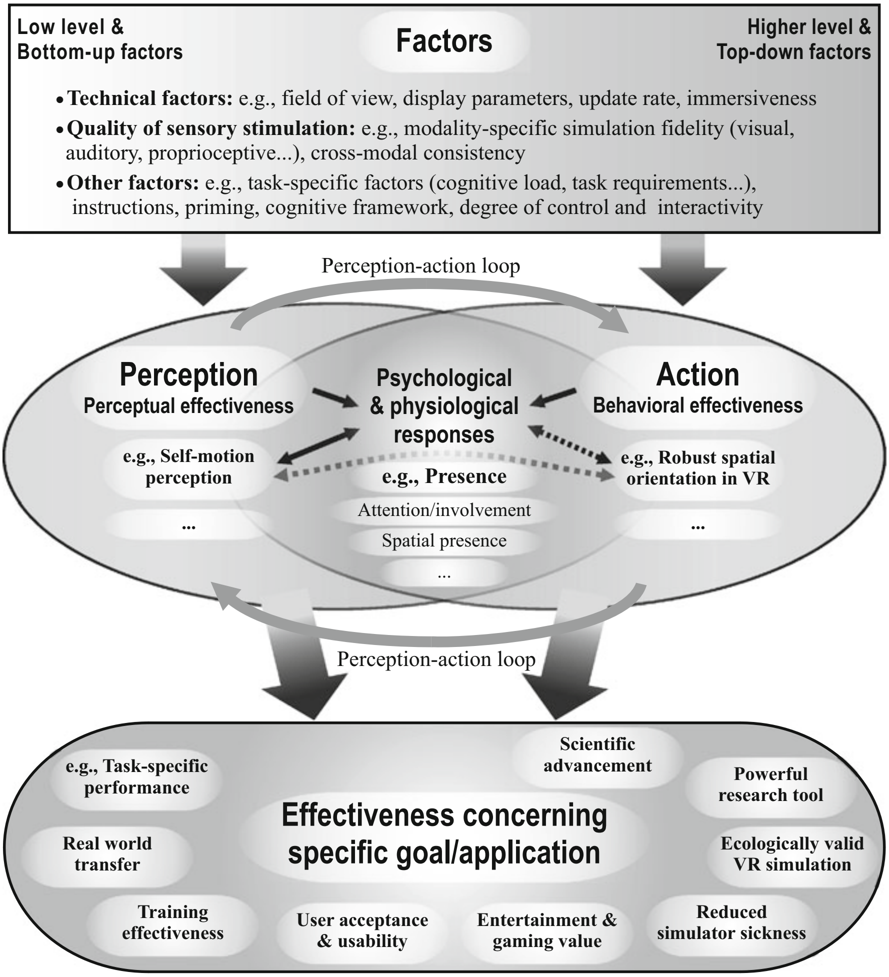

Fig. 9.7 Tentative conceptual framework that sketches how different factors that can be manipulated for a given VR/research application (*top box*) might affect the overall effectiveness with respect to a specific goal or application (*bottom box*). Critically, we posit that the factors affect the overall goal not (only) directly, but also mediated by the degree to which they support both the perceptual effectiveness and behavioural effectiveness and the resulting perception-action loop (*middle box*). There are a number of physiological responses (e.g., fear or pleasure) and psychological responses (e.g., higher-level emergent phenomena like spatial presence or involvement) that can potentially both affect and be affected by the users' perception and action

considered in the context of both their ***perceptual effectiveness*** (e.g., how they contribute to the perceived self-motion) and their ***behavioural effectiveness*** (e.g., how they contribute by empowering the user to perform a specific behaviour like robust and effortless spatial orientation and navigation in VR), as sketched in Fig. 9.7, middle box.

Perception and action are interconnected via the ***perception-action loop***, such that our actions in the environment will also change the input to our senses. State-of-the art VR and human-computer interface technology offer the possibility to provide highly realistic multi-modal stimuli in a closed perception-action loop, and the different contributing factors summarized in the top box of Fig. 9.7 could be evaluated in terms of the degree to which they support an effective perception-action loop (Ernst and Bülthoff 2004).

Apart from the perceptual and behavioural effectiveness, we propose that psychological and physiological responses might also play an important role. Such responses could be emergent and higher-level phenomena like spatial presence, immersion, enjoyment, engagement, or involvement in the VE, but also other psychological responses like fear, stress, or pleasure on the one hand and physiological responses like increased heart rate or adrenalin level on the other hand. In the current framework, we propose that such psychological and physiological responses are not only affected by the individual factors summarized in the top box in Fig. 9.7, but also by our perception and our actions themselves. Slater et al. (1998) demonstrated, for example, that increased body and head motions can result in an increased presence in the VE. The comparison between Experiment 1 and 2 suggests that presence might also be affected by the strength of the perceived self-motion illusion.

Conversely, certain psychological and physiological responses might also affect our perception and actions in the VE. Experiment 1 and 2 suggest, for example, that the degree of presence in the simulated scene might also affect self-motion perception. Our actions and behaviours in a VE might, however, also be affected by our psychological and physiological responses. Von der Heyde and Riecke proposed, for example, that spatial presence might be a necessary prerequisite for robust and effortless spatial orientation based on automatic spatial updating or certain obligatory behaviours like fear of height or fear of narrow enclosed spaces (von der Heyde and Riecke 2002; Riecke 2003).

In the context of presence, we have seen that different aspects of presence interrelate differentially to different perceptual aspects (see factor analysis and correlations in Sect. 9.4.5). Thus, it might be conceivable that different aspects of presence (e.g., involvement vs. spatial presence) also relate differentially to specific behavioural and task-specific aspects. In general, more fine-grained analyses seem to be necessary in order to reveal such connections between presence and other measures such as vection, as we were able to show in our analysis.

In summary, we posit that our understanding of the nature and usefulness of the cognitive factors and higher-level phenomena and constructs such as presence and immersion might benefit if they are embedded in a larger conceptual framework, and in particular analysed in terms of possible relations to perceptual and behavioural aspects as well as goal/application-specific effectiveness. Similar benefits are expected if other higher-level phenomena are analysed in more detail in the context of such a framework.

9.7 Outlook

A growing body of evidence suggests that there is a continuum of factors that influence the perceptual and behavioural effectiveness of VR simulations, ranging from perceptual, bottom-up factors to cognitive, top-down influences. To illustrate this, we reviewed recent evidence suggesting that self-motion illusions can be affected by a wide range of parameters including attention, viewing patterns, the perceived depth structure of the stimulus, perceived foreground/background distinction (even if there is no physical separation), cognitive-perceptual frameworks, ecological validity, as well as spatial presence and involvement. While some of the underlying research is still preliminary, findings are overall promising, and we propose that these issues should receive more attention both in basic research and applications.

These factors might 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 behavioural effectiveness. Compared to other means of increasing the convincingness and effectiveness of self-motion simulations like increasing the visual field of view, using a motion platform, or building an omni-directional treadmill, cognitive factors can often be manipulated rather easily and without much cost, such that they could be an important step towards a lean and elegant approach to effective self-motion simulation (Riecke et al. 2005c, e; Riecke and Schulte-Pelkum 2013; Riecke 2011). This is nicely demonstrated by many theme park rides, where a conducive cognitive-perceptual framework and expectations are set up already while users are standing in line (Nunez and Blake 2003; Nunez 2003). Although there is little published research on these priming phenomena in theme parks, they likely help to draw users more easily and effectively into the simulation and into anticipating and "believing" that they will actually be moving. Thus, we posit that an approach that is centred around the perceptual and behavioural effectiveness and not only the physical realism is important both for gaining a deeper understanding in basic research and for 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". That is, a virtual reality that is readily accepted as an alternate "reality" that enables us to perceive, behave, and more specifically locomote and orient as easily and effectively as we do in our real environment.

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