

Using the perceptually oriented approach to optimize spatial presence & ego-motion simulation

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This chapter is concerned with the perception and simulation of ego-motion in virtual environments, and how spatial presence and other higher cognitive and top-down factors can contribute to improve the illusion of ego-motion 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, not yet allow for natural, real-life-like interaction between the user and the virtual environment. One crucial shortcoming in current VR is the insufficient and often unconvincing simulation of ego-motion, which frequently causes disorientation, unease, and motion sickness. We posit that a realistic perception of ego-motion in VR is a fundamental constituent for spatial presence and vice versa. Thus, by improving both spatial presence and ego-motion perception in VR, we aim to eventually enable performance levels in VR similar to the real world for basic tasks, e.g., spatial orientation and distance perception, which are currently very problematic cases. Users frequently get lost easily in VR while navigating, and simulated distances appear to be compressed and underestimated compared to the real world (Witmer & Sadowski, 1998; Chance, Gaunet, Beall, & Loomis, 1998; Creem-Regehr, Willemsen, Gooch, and Thompson, 2003; Knapp, 1999; Thompson, Willemsen, Gooch, Creem-Regehr, Loomis, & Beall, 2004, Stanney, 2002).

The overall goal of the EU-funded project on “Perceptually Oriented Ego-Motion Simulation” (POEMS-IST-2001-39223, see www.poems-project.info) has been to take first steps towards establishing a lean and elegant ego-motion simulation paradigm to achieve convincing ego-motion perception and effective ego-motion simulation in VR, without (or while hardly) moving the user physically. The ultimate goal is to achieve cost-efficient, ego-motion simulation that enables compelling perception of self-motion and quick, intuitive, and robust spatial orientation while travelling in VR, with performance similar to the real world.

The POEMS approach to tackle this goal was to concentrate on perceptual aspects and task-specific effectiveness rather than aiming for perfect physical realism (see Section 2). This approach focuses on multi-modal stimulation of our senses, where vision, auditory information, and vibrations let users perceive that they are moving in space. Furthermore, top-down or high-level phenomena like spatial presence and reference frames are utilized to improve the effectiveness of ego-motion simulation. It is well-known that quite compelling ego-motion illusions can occur both in the real world and in VR. Hence, the investigation of such ego-motion illusions in VR was used as a starting point for improving self-motion simulations in VR.

Spatial presence and immersion occupy an important role in this context, as they are expected to be an essential factor in enabling robust and effortless spatial orientation and task performance. Furthermore, according to our current spatial orientation framework (von der Heyde & Riecke, 2002, Riecke & von der Heyde, 2002), we propose that spatial presence and immersion are necessary prerequisites for quick, robust, and effortless spatial orientation behaviour and also for automatic spatial updating in particular. Thus, increasing spatial presence and immersion would in turn be expected to increase the overall convincingness and perceived realism of the simulation, bringing us one step closer to our ultimate goal of real world-like interaction with and navigation through the virtual environment.

In our psychophysical experiments, the observed data suggest a direct relation between spatial presence and the strength of the self-motion illusion in VR: Experimental data from two ego-motion perception experiments will be reported in more detail in Section 3 and 4, where a systematic link between spatial presence ratings and ego-motion perception responses was observed. This finding is important, both from an applied perspective of self-motion simulation, and for our understanding of presence and of self-motion perception.

1 Motivation

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 natural experience of ego-motion in VR. This limits 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 in the field of ego-motion simulation.

Current high-end motion simulators are rather costly and large, and often require large spaces and expert technical personnel to maintain and operate the simulator. 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. 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. 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.

Apart from being rather large and costly, the most common problem associated with current motion simulators is the frequent occurrence severe motion sickness (Bles, Bos, de Graaf, Groen, & Wertheim, 1998; Guedry, Rupert, & Reschke, 1998; Kennedy, Lanham, Drexler, Massey, & Lilienthal, 1997; Stanney, Mourant, & Kennedy, 1998). Furthermore, users get easily disoriented and lost while navigating through virtual environments (e.g., Chance et al., 1998, Ruddle & Jones, 2001). It is not yet fully understood where exactly these problems arise from, although Chance et al. (1998) demonstrated that allowing for physical rotations in VR can reduce those problems somewhat.

The perceptually-oriented approach pursued by POEMS aims towards a lean and elegant ego-motion simulation paradigm by focussing on perceptual effectiveness, as opposed to the more traditional approach which strives to achieve physical realism. That is, instead of for example trying to realistically simulate physical forces using a motion platform, we investigate whether the overall simulation effort can be reduced by optimally and consistently stimulating the other senses contributing to ego-motion perception (mainly visual, auditory, and tactile/vibrational) – which can typically be simulated more easily and with less financial and technical effort.

This chapter will provide a brief literature overview on self-motion illusions in general and initial results demonstrating 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 ego-motion perception and might thus be important factors that should receive more attention when aiming for a lean and elegant ego-motion simulation paradigm.

2 Beyond the engineering approach: Perceptually and effectiveness-oriented approaches to VR simulation

Even with the amazing recent improvements of VR soft- and hardware, it is still impossible (and quite cost-inefficient) to try to simulate all modalities with physical realism. So how can we “cheat intelligently and get away with it?” One approach is to rely heavily on multimodal presentation, as some modalities can capture or even override others (e.g., “visual capture”). Physically moving the observer is for example quite costly and potentially dangerous. Hence, it makes sense to reduce the physical motion part of a simulation to the absolute minimum that is still sufficient for providing a convincing sensation of ego-motion and allow for the desired task-specific performance. In order to find out what the absolutely required information is, however, we need to perform well-controlled psychophysical experiments.

2.1 Perceptually-oriented computer graphics rendering

The commonly used and widely accepted way to evaluate for example the quality of computer graphics is to just look at them and “see which one is better”. A good example for a more sensible approach is the selective rendering algorithm developed at Alan Chalmers’ lab at the University of Bristol, UK. The main idea is to exploit some particularities of the human visual system to optimise the way computer generated images and animations are rendered. The rendering quality is lowered in particular parts of the image, but this goes unnoticed for the user (Cater, Chalmers, & Ward, 2003).

It is commonly believed that the human visual system sees everything very accurately. However, this is only true within a central field of view (FOV) of about 2 degrees, the fovea. The quality of the retinal image rapidly decreases in the peripheral area to the point where only a coarse representation of our environment is actually captured by the retina. There is also evidence that, at a higher cognitive level, the visual system only selects and processes information that is relevant at that point of time and can completely ignore large parts of the visual field. This is commonly called “inattention blindness”: a person will completely fail to notice obvious details of a presented scene if they are not attending them (Mack & Rock, 1998). This is also true for changes in a scene when they happen in an unattended area (Simons & Levin, 1998). People will fail to notice what changed, or even that anything changed at all (“change blindness”).

Humans build a visual representation of their surroundings by making saccadic eye movements to the different objects that are around. We attend each of them for a very short time, and then move to the next one. The visual system decides what to attend partly from bottom-up features. Itti & Koch (2000) have developed a way of creating saliency maps from images, which show which areas are more likely to be attended to (“salient areas”)

and in which order, based on low-level, bottom-up processed features (intensity, brightness and orientation). Yee proposed a model that also includes motion in the scene (Yee, Pattanaik, & Greenberg, 2001). Cater et al. showed that visual attention is also based on top-down processes (Cater, Chalmers, & Ledda, 2002): It is possible to predict with great accuracy which areas of an image a person will attend to by giving them a specific task, such as counting a certain type of object in a scene. Unless given much more time than needed, participants are able to quickly give an accurate result, but will completely fail to answer questions about other details of the image. Hence, whenever possible, top-down features should be taken into account to build the saliency map.

These interesting features of the visual system can be exploited to save time during the rendering of computer generated images by only displaying the areas of interest with high fidelity. Being able to predict which areas of a scene are perceptually important will help setting a limit to how much detail is needed in different areas of the display, thus greatly reducing the rendering time. Cater et al. mention that for one of their animations, rendering the complete scene at the highest level of details took seven times longer than the optimised version, with the same perceptual result (Cater et al., 2003).

The selective rendering approach nicely illustrates how specific limitations in VR technology can be overcome in an elegant manner by exploiting particularities of our perceptual system in a cost-efficient way, instead of aiming for a highest degree of physical realism. Furthermore, this example shows how top-down influences can have a strong effect on perceptual processes in virtual environments, and how these top-down influences can be utilized to improve VR simulations.

This principle is, for instance, used for audio compression, notably by the now very popular MP3 format. In order to reduce file size, audio data that will not be heard by most people is simply removed and the file is then compressed in a standard, non-lossy manner. The effect that makes people not hear those sounds is called masking. There are two types of masking: simultaneous masking (for example, when two sounds are played together, the loudest one may mask the other one), and temporal masking (when two sounds are played one after another but temporally very close, one will not be able to hear the second one). The result is that, for a comparable perceived quality, the size of an MP3 file is about 10 times smaller than its uncompressed equivalent.

2.2 The challenge of ego-motion simulation

The technical limitation in ego-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 (Conrad, Schmidt, & Douvillier, 1973). The tuning of these “washout filters” is a tedious business, and is typically done manually in a trial-and-error approach where experienced evaluation subjects collaborate with washout filter experts who iteratively adjust the filter parameters until the evaluation subject is satisfied.

While this might be feasible for some 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 classic approach. Such problems are evident for example in many flight and driving applications, where training in the simulator has been shown to cause a misadapted behaviour that can be problematic in the corresponding real-world task (Boer, Girshik, Yamamura & Kuge, 2000; Mulder, van Passen & Boer, 2004; Wood, 1983; Bailey, Knotts, Horowitz & Malone, 1987; Brandon, Glaab, Brown & Philips, 1995; Dearing, Schroeder, Sweet & Kaiser, 2001; Field, Armor & Rosito, 2002; Lee, Rodchenko, Zaichik & Yashin, 2003; Burki-Cohen, Go, Chung, Schroeder, Jacobs & Longridge, 2003; Zaichik & Cardullo, 2003). Recent attempts to formalize comprehensive theory of motion perception and simulation in VR were, however, limited by our lack of a comprehensive 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 presentation and washout filters in particular (Grant & Reid, 1997a,b, Gouverneur, Mulder, Van Paassen, Stroosma & Field, 2003; Hosman, 1999; Mulder et al., 2004; Pouliot, Gosselin & Nahon, 1998; Wu & Cardullo, 1997; Zeyada & Hess, 2003).

Here, we propose to go beyond the classic approach by including an interdisciplinary approach that is based on the careful psychophysical evaluation of the perceptual and task-specific effectiveness of both the within-modality and cross-modal rendering. Such an approach has successfully been employed in the POEMS EU-project on “Perceptually Oriented Ego-Motion Simulation” and will be extended and refined further. Such an approach is based on the notion that it fundamentally does not matter how much physical realism is contained in the rendered stimuli, as long as users *perceive* what is intended (“*perceptual effectiveness*”) and act appropriately for a given task (“*task-effectiveness*”). The MP3 encoding standard illustrates the power and elegance of such an approach: There, a deep understanding of the complex human perceptual system enabled the

developers to focus on rendering what can actually be perceived by the human auditory system in high quality while omitting what cannot be perceived anyways. A similar approach will be employed and further extended to optimize VR simulations in terms of spatial presence, convincingness, and ego-motion perception and simulation.

Such a perceptually and effectiveness-oriented approach can be employed for individual sensory modalities as well as the display medium itself where appropriate. In terms of visual displays, for example, it is important to carefully evaluate different display systems in terms of their effectiveness and usability for a given task. Recent studies showed for example that especially head-mounted displays (HMDs) often lead to systematic distortions of both perceived distances and turning angles (Bakker, Werkhoven, & Passenier, 1999, 2001; Creem-Regehr et al., 2003; Riecke, Schulte-Pelkum, & Bülthoff, 2005a; Schulte-Pelkum, Riecke, von der Heyde, & Bülthoff, 2004). 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 20m for targets in the real world (Loomis, da Silva, Fujita, & Fukusima, 1992; Loomis, Da Silva, Philbeck, & Fukusima, 1996; Philbeck & Loomis, 1997; Rieser, Ashmead, Talor, & Youngquist, 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., 2003; Witmer & Sadowski, 1998; Knapp, 1999; Thompson et al., 2004; Willemsen, Gooch, Thompson, & Creem-Regehr, submitted). 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 feet (Witmer & Kline, 1998). A similar overestimation and compression in response range for HMDs has recently been observed for visually simulated rotations (Riecke et al., 2005a). So far, only projection setups with horizontal field of views of 180° or more could apparently enable close-to-veridical perception (Plumert, Kearney & Cremer, 2004; Riecke et al., 2005a; Riecke, van Veen, & Bülthoff, 2002), even though the FOV alone is not sufficient to explain the systematic misperception of distances in VR (Knapp & 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 ego-motion simulation.

2.3 Literature overview on the perception of illusory self-motion (vection)

In this section, we provide a brief overview over the most important findings about the self-motion illusion. For comprehensive reviews, see Dichgans & Brandt (1978) and Howard (1986). Hettinger (2002) gives an overview about VR-related work on the self-motion illusion.

When stationary observers view a moving visual stimulus that covers a large part of the field of view (FOV), they can experience a very compelling 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 perceive that the train we are sitting in is starting to move. This phenomenon of illusory self-motion has been termed “vection”, and it has been investigated for well over a century (Mach, 1875). 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. 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.

In a typical vection experiment, participants are seated inside a rotating drum painted with black and white vertical stripes inside, 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 physically counter-rotate the seat until the perceived self-rotation vanishes. Traditionally, the occurrence of this illusion has been thought to depend mainly on bottom-up features of the visual stimulus. We will now present the most important parameters that have been found to influence vection in some more detail.

2.3.1 Size of the visual FOV

Using an optokinetic drum, Brandt, Dichgans, and Koenig (1973) found that visual stimuli covering large FOVs induce stronger circular vection with shorter onset latencies, and that stimulation of the entire FOV results in strongest vection. Limiting the FOV systematically increased onset latencies and reduced vection intensities. It was also found that a 30° stimulus viewed in the periphery of the visual field induces strong vection at comparable levels as full field stimulation, whereas the identical 30° stimulus viewed in the central FOV did not induce vection. This observation led to the conclusion of “peripheral dominance” for self-motion perception,

and the central FOV was thought to be more important for the perception of object 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. Interestingly, pilot experiments had revealed that in order to perceive self-motion, participants had to believe that they were in an environment where they could actually be moved in the direction of perceived vection. Accordingly, participants were standing on a movable booth and looked out of a window to view the optic flow pattern. This observation is very interesting, since it indicates a cognitive influence on vection, and we will elaborate on this in Section 5. Howard and Heckmann (1989) proposed that the reason Brandt et al. (1973) found a peripheral dominance was 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 notion in their experiment by placing the moving visual stimulus either in front or in the back of the plane of the rotating drum. Their data showed that if a central display is perceived to be in the background, it will induce vection. Thus, the original idea of peripheral dominance for self-motion perception should be reassessed.

However, the general notion that larger FOVs are more effective to induce vection does hold true. For virtual reality applications, this means that larger displays are better suitable for inducing a compelling illusion of self-motion.

2.3.2 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 & Heckmann, 1989; Howard & Howard, 1994; Ohmi, Howard, & Landolt, 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 & Howard, 1994). Dichgans and Brandt (1978) have proposed that this effect might be due to our inherent assumption of a stable environment: 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 is 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 that partly occlude a moving background will increase vection (Howard & Howard, 1994), and that a foreground that moves slowly in opposite direction to the background will also facilitate vection (Nakamura & Shimojo, 1999). In Section 4, we will present new data from our experiments that extend this finding and discuss implications for self-motion simulation from an applied perspective.

2.3.3 Spatial frequency of the moving visual pattern

Diener et al. (1976) observed that moving visual patterns with high spatial frequencies are perceived to move faster than similar visual patterns with 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 section 2.3.1) and shows that both high- and low 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 beneficial in the central FOV, and that stimuli in the periphery might be rendered at lower resolution and fidelity. This goes in line with the perceptually oriented selective rendering algorithm that was mentioned in section 2.1.

2.3.4 Optical velocity of the visual stimulus

Howard (1986) and Brandt et al. (1973) reported that the intensity and perceived speed of self-rotation in circular vection is linearly proportional to the optical velocity of the optokinetic stimulus up to values of approximately $90^\circ/\text{s}$. As detailed in section 2.3.3, the perceived velocity interacts with the spatial frequency of

the stimulus. 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 vestibular threshold results in faster vection onset (Wertheim, 1994). This might be due to different methods used: While Brandt et al. (1973) accelerated the optokinetic drum in darkness to a constant velocity and measured the 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.

2.3.5 Eye movements

It has long been recognized that eye movements influence the vection illusion. Mach (1875) was the first to report that if observers fixate a stationary target, vection will develop faster than when the eyes follow the stimulus. This finding has been replicated many times (e.g., Brandt et al., 1973; Becker, Raab, & Jürgens, 2002). Becker et al. (2002) 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 riding a bus. In other conditions, they either had to voluntarily suppress the OKN by fixating a stationary target that was presented on top of the moving stimulus, or stare through the moving stimulus. Results showed that vection developed fastest with the eyes fixating a stationary fixation point than when participants stared through the stimulus, and vection took longest to develop when the eyes moved naturally, following the stimulus motion.

2.3.6 Spatialized auditory cues and multimodal consistency

Almost all of the vection literature has been concerned with visually induced vection. Vection induced by moving acoustic stimuli has therefore received little attention, even though Lackner (1977) demonstrated that a rotating sound field generated by an array of loudspeakers can induce vection in blindfolded participants. Recent experiments by the POEMS project 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, Västfjäll, & Kleiner, 2004; Riecke, Västfjäll, Larsson, & Schulte-Pelkum, 2005c; Våljamäe, Larsson, Västfjäll, & Kleiner, 2004, 2005). Several factors were found to enhance auditory vection (see the chapter by Larsson, Våljamäe, Västfjäll, & Kleiner in this volume for more information): Both the realism of the acoustic simulation and the number of sound sources was found to enhance vection. Larsson et al. (2004) observed also a higher cognitive or top-down influence: “Acoustic landmarks”, which are sound sources that are typically associated with stationary objects (e.g., church bells) were more suitable for inducing auditory vection than artificial sounds (e.g., pink noise) or sounds that are typically related to moving objects (e.g., foot steps). It is important to keep in mind, however, that auditory vection occurs only in about 25-60% 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. A recent study by Riecke, Schulte-Pelkum, Caniard, and Bühlhoff (2005b) demonstrated, however, that 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. This suggests that multi-modal consistency might be beneficial for the effectiveness for self-motion simulations. This notion is supported by Wong & Frost (1981), who demonstrated that circular vection is facilitated when participants are provided with an initial physical rotation (“jerk”) that accompanies the visual motion onset. 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. In a recent study on circular vection in VR, simply adding vibrations to the participants’ seat and floor plate during the visual motion proved already to be sufficient to enhance vection significantly (Riecke et al., 2005b; Schulte-Pelkum, Riecke, & Bühlhoff, 2004a). Similarly, recent results of the POEMS project demonstrated that auditory vection can also be facilitated by added vibrations, both for translational and rotational movements (Våljamäe, Larsson, Västfjäll, & Kleiner, 2005a). A comparable enhancement of auditory vection was observed when adding infrasound (15Hz).

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.

2.4 Beyond physical realism – Higher-level cognitive and top-down factors affecting the ego-motion sensation in VR

In the following, we will provide experimental data showing how spatial presence and other cognitive or top-down aspects might be exploited to increase the subjective fidelity of VR simulation beyond the classic (technology-centred) approach. There is an abundance of studies in the literature investigating and demonstrating a bottom-up contribution of various physical stimulus parameters to ego-motion perception. It is conceivable, however, that ego-motion perception can also be influenced by expectations as well as the interpretation or associated meaning of the stimuli (i.e., higher-level cognitive and top-down effects). We will provide experimental evidence here that such effects can indeed play a strong role in the perception of ego-motion. Especially the interpretation and meaning associated with particular stimuli proved to affect ego-motion perception consistently. Furthermore, the congruence and consistency of the motion metaphor and simulated scene can be important (e.g., Riecke et al., 2005c).

As these manipulations have typically rather small technical effort associated, such an approach can assist in reducing the overall simulation effort and costs, thus bringing us closer to the goal of a lean and elegant – but still effective – ego-motion simulation paradigm and setup. One leading hypothesis is that spatial presence and immersion should increase the overall naturalness and believability of the simulation, which might in turn be instrumental in increasing the overall effectiveness of the simulation. This hypothesis can be tested by varying spatial presence and monitoring the influence on the effectiveness of the simulation. Conversely, if our hypothesis is confirmed, this might allow us to quantify and compare presence in different scenarios indirectly by testing how much the simulation effectiveness has been increased. Recent studies provided initial evidence that the mental framework and pre-conceptions about the possibility/plausibility of physically moving do indeed have an influence on the perception of (illusory) self-motion (Lepecq, Giannopulu, & Baudonniere, 1995; Palmisano & Chan, 2004; Riecke et al., 2005c; Schulte-Pelkum et al., 2004a). In many applications and learning scenarios in particular, task demands and high stress level might reduce participants' susceptibility to inconsistencies in the cross-modal consistency of the motion simulation, which could be exploited to increase the effectiveness of ego-motion simulation. Other factors that might be influential are the enjoyment and engagement offered by the simulation. Guiding attention and intentions (goals) of the users is one of the strategies that could be useful to mask minor imperfections in the simulation, as has been demonstrated in a variety of striking "change blindness" demonstrations.

Finally, the influence of reference frames on ego-motion simulation could be beneficial for many VR applications: All VR simulations have the common challenge of convincing the users that they should feel present in and interact with the simulated environment while more or less ignoring the physical simulation setup. Carefully designing the simulator setup and paradigm is expected to have a positive influence on this potential conflict between simulated and physical reference frame, as many entertainment applications (e.g., amusement park fun rides) suggest. Thus, it is expected that presence and overall effectiveness of ego-motion simulation can be enhanced by providing users with a consistent mental framework and motion paradigm that does not distract them from the simulation, but rather increases their interest and motivation. We expect, for example, performance benefits if users can be convinced to interpret the physical simulation setup as their "cockpit" instead of a stationary video projection setup. Hence, care should be taken that the physical simulator setup will be accepted as a "window onto the virtual world".

3 Experiment 1: Relations between spatial presence, scene consistency and ego-motion perception

The fact that the majority of studies onvection have focused on bottom-up parameters that affectvection means that relatively little work has been carried out to examine how higher-level and top-down processes, like the semantic interpretation of the moving stimulus, can affectvection. The possibility that psychological factors can affect the probability of sensingvection or at least modulate its onset latency and strength has been largely neglected by researchers. Nevertheless, we posit that such higher-level factors could play an important role in the perception ofvection. For instance, it could be the case thatvection is perceived because of our inherent assumption of a stable environment (Dichgans & Brandt, 1978). That is, while during the course of our daily lives we typically move around in the environment, it is only rarely the case that a large portion of our surroundings moves relative to us. As a result, when this happens – in experimental settings or in some rare natural occasions – we are more inclined to attribute the movement to ourselves instead. Perhaps this is why the background of avection-inducing stimulus is typically the dominant determinant of the presence ofvection and modulator of the strength ofvection. 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 & Shimojo, 1999).

If indeed vection depends on the assumption of a stable environment, then one would expect that the sensation of vection should be enhanced if the presented visual stimulus (e.g., a virtual environment) is “accepted” as a real world-like stable reference frame. That is, we posit that vection in a simulated environment should be enhanced if participants feel immersed and 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. To the best of our knowledge, this hypothesis has not been examined before. We are only aware of a brief commentary paper which stressed the importance of an ecological context and a naturalistic optic array for studying self-motion perception (Wann & Rushton, 1994). Apart from that, past research on vection has traditionally used abstract stimuli like black and white striped patterns or random dot displays. The goal of the present study is to determine whether vection can be modulated by the nature of the stimulus depending on whether it comprises of a natural scene that allows for the occurrence of presence or not¹. 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, labor-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.

3.1 Hypotheses

Participants in our experiment experienced circular vection induced by two types of stimuli: a photorealistic image of a natural scene and scrambled versions of it. Various scrambled version of the stimulus were created by scrambling image parts either in a mosaic-like manner or by slicing the original image horizontally and randomly reassembling it (cf. Figure 2). Questionnaires administered after the experiment assessed the extent of experienced presence for each experimental stimulus. The purpose of the scene scrambling was to decrease global scene consistency² while only slightly changing image statistics (bottom-up contributions, see also hypothesis 2 below). The experimental design was based on the assumption that global scene consistency should increase the believability of the visual stimulus (higher-level effect), as it allows for locomotion and spatial presence in the simulated scene. Conversely, scene scrambling should reduce believability and spatial presence in the virtual environment (i.e., the subjective experience of “being there” in one place or environment, even when one is physically situated in another (Witmer & Singer, 1998), as only the globally consistent stimulus can naturally be recognized or interpreted as a three-dimensional scene, which might in turn allow for actions such as locomotion through the scene. These are all highly cognitive or top-down processes. That is, spatial presence was expected to be highest in the globally consistent (unscrambled) scene and decreasing as scrambling severity increased. Two hypotheses were examined here:

1. Global scene consistency & presence (higher-level factors): Based on the stable environment hypothesis, we would predict that global scene consistency and presence should be important factors for vection, as they are expected to increase the believability of the visual stimulus. Hence, the globally consistent (unscrambled) stimulus depicting a natural scene should enhance vection, compared to any of the scrambled or sliced stimuli which are all globally inconsistent, ideally in terms of all response measures. If vection depended only on global scene consistency and presence, the various scrambled stimuli should not differ from each other in either the presence ratings or the vection measures. (i.e., $A > B = C = D$ & $a > b = c = d$; see Figure 2).

2. Number of vertical high-contrast edges (bottom-up factor): Apart from the higher-level influence discussed above, the mosaic-like scene scrambling also affected physical stimulus properties or so-called bottom-up factors: The mosaic-like scrambled stimuli contained additional vertical high-contrast edges – a bottom-up factor that is known to increase perceived stimulus speed (Distler, 2003) and vection (Dichgans & Brandt, 1978). Hence, if these bottom-up factors dominate over higher-level factors like presence, scene consistency, and object recognition, the scrambled stimuli would be expected to increase vection, compared to the sliced stimuli which did not contain such additional vertical edges (i.e., $B > b$, $C > c$, $D > d$; see Figure 2).

¹ This section is based in part on a conference paper by Riecke, Schulte-Pelkum, Avraamides, von der Heyde, & Bülthoff, (2005e)

² Global scene consistency refers here to the coherence of scene layout that is consistent with our natural environment, where for example houses do not float in mid-air, but are arranged meaningfully next to one another.

3.2 Methods

3.2.1 Participants

Twelve naive participants (four female) participated in the study in exchange of monetary compensation. All participants had stereo vision and normal or corrected-to-normal vision.

3.2.2 Stimuli and Apparatus

Participants were comfortably seated at a distance of 1.8m from a curved projection screen on which the rotating visual stimuli (20°/s or 40°/s) were displayed. See Figure 1 for a depiction of the different stimuli used. The experiment followed a 2 (session: mosaic, slices) \times 4 (scrambling severity: intact, 2, 8, 32 mosaics/slices) \times 2 (rotation velocity: 20°/s, 40°/s) \times 2 (turning direction) within-subject factorial design with two repetitions per condition. The projection screen had a curvature radius of 2m, and the simulated FOV was set to 54° \times 45° to match the physical FOV. Vection responses were collected using a force-feedback joystick that was mounted in front of the participants at a comfortable distance³.

3.2.3 Procedure

Participants were instructed to pull the joystick in the direction of their perceived self-motion as soon as it was sensed. The time interval between the onset of stimulus rotation and the first deflection of the joystick indicated the vection onset time and was the primary dependent measure. Participants were also asked to deflect the joystick more the stronger the perceived self-motion became; this allowed recording the time course of vection intensity. Finally, at the end of each trial participants were asked to provide a “convincingness rating” of perceived self-motion by moving a lever next to the joystick to select one of the 11 possible steps of a 0%-100% rating scale. The value of 0% corresponded to “no perceived motion at all” (i.e., perception of a rotating stimulus and a stationary self) and that of 100% to “very convincing sense of vection” (i.e., perception of a stationary stimulus and a rotating self).



Figure 1: Participant seated in front of curved projection screen displaying a view of the Tübingen market place.

Participants were instructed to watch the stimuli “as relaxed and naturally” as possible. We did not use any fixation point, even though it is known that a fixation point reduces vection onset times (Becker et al., 2002). The main reason was that from an applied perspective for ego-motion simulation, it is more relevant to investigate how one can induce vection under natural viewing conditions, i.e., without a fixation point.

³ A more detailed description of this experiment can be found in Riecke et al., (2005e).



Figure 2: Top: 360 roundshot of the Tübingen Market Place. Middle: $54^\circ \times 45^\circ$ view of the 4 stimuli used in one session: Original image and 2, 8, and 32 slices. Bottom: $54^\circ \times 45^\circ$ view of the 4 stimuli used in the other session: Original image and 2x2, 8x8, and 32x32 mosaics per $45^\circ \times 45^\circ$ FOV. (Top image reprinted from Riecke et al., 2004 & Riecke et al., 2005b (©2005 IEEE) with permission).

3.3 Results

The data for vection onset time, convincingness of the self-motion illusion, and vection intensity are summarized in Figure 4, interleaved with the data from the next experiment for easier comparability in subsection 4.2.3. Repeated-measures ANOVAs were performed for the three dependent variables using session, scrambling severity, and rotation velocity as factors. Furthermore, correlation analyses between vection measures and the presence questionnaire data were performed.

3.3.1 Vection onset time

The 3-way ANOVA for vection onset time revealed two significant main effects. First, participants were faster at reporting the onset of vection when the stimuli rotated at $40^\circ/\text{s}$ than at $20^\circ/\text{s}$, $F(1,10)=23.9$, $p<.001$. Second, vection onset times varied depending on scrambling severity, $F(3,30)=6.23$, $p<.01$. More specifically, participants indicated the onset of vection faster with the intact stimuli than any of the scrambled stimuli.

3.3.2 Vection intensity

As in the vection onset time analysis, the only significant statistics for vection intensity were the main effects for rotation velocity and scrambling intensity $F(1,10)=42.0$, $p<.001$ and $F(3,30)=8.29$, $p<.001$, respectively). Participants indicated stronger vection for stimuli rotating at $40^\circ/\text{s}$ than at $20^\circ/\text{s}$. Furthermore, vection was rated as stronger for the intact stimulus than any of the 2, 8, or 32 slices/mosaics.

3.3.3 Convincingness of vection

The analyses for the convincingness ratings revealed effects that paralleled those of the other two measures. Participants rated as more convincing the illusory self-movement produced by stimuli rotating at $40^\circ/\text{s}$ than at $20^\circ/\text{s}$ ($F(1,10)=23.7$, $p=.001$). Moreover, they rated vection as being more convincing for the globally consistent stimulus than any of the other stimuli ($F(3,30)=41.4$, $p<.001$; all pairwise p 's $<.001$). There was also a significant difference between the 2 and the 8 slices/mosaics ($t(11)=-4.16$, $p<.01$).

3.3.4 Questionnaires

After each session, participants completed the 14-item Igroup Presence Questionnaire IPQ, (Schubert, Friedmann, & Regenbrecht, 2001) for each of the four scenes that were presented in the experimental session. In our sample, the IPQ showed high reliability ($\alpha = .91$). To examine the structure and constituent elements of the presence questionnaire, we analyzed similarities and correlations between the responses to the different questions of the IPQ using a factor analysis. The factor analysis revealed a 2-dimensional structure of the presence questionnaire: Factor 1 contained items about realism of the simulated scene and spatial presence (e.g., sense of acting 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). Factor 1 and 2 correspond to the bottom right and left plots, respectively, in Figure 5.

Mean presence scores obtained with the IPQ were computed for each level of the sliced or mosaic scenes (see Figure 5, top left plot). A repeated-measures ANOVA showed a significant effect only for the number of slices ($F(3,18)=21.5$, $p=.001$). A post-hoc analysis showed that only the presence ratings of the intact market scene differed significantly from all other levels (Bonferroni-corrected $p=.003$), but no significant differences between the 2, 8, and 32 slices were found (see Figure 5). That is, two slices were enough to impair presence significantly, and no further decrease in presence was observed for the 8 and 32 slices. Mean presence scores for each of the four original subscales of the IPQ (realism, presence, space, and involvement) and also of the compound scales that were merged according to the factor analysis (factor 1 = “spatial presence” and factor 2 = “involvement”) are shown in Figure 5.

In the next step, we investigated how presence in the simulated scene related to the different aspects of the self-motion illusion by performing correlation analyses between the mean presence scores and the three measurands from the vection experiment (vection onset time, vection intensity, and convincingness). **Error! Reference source not found.** shows the paired-samples correlations (r) and the corresponding p -values. For a more detailed analysis, the factor values from the factor analysis of the presence ratings for each level were correlated with the experimental measures. The two factors were interpreted as “spatial presence” and “attention/involvement” (captions “factor 1: spatial presence” and “factor 2: involvement”).

Interestingly, there was an asymmetry in the correlation results: Convincingness ratings correlated highly with the factor 1 (spatial presence) but not with factor 2 (involvement). Conversely, vection onset time was negatively correlated with factor 2 (involvement), but not with factor 1 (spatial presence). Vection intensity was only moderately correlated with factor 2 (involvement), but not at all with factor 1 (spatial presence). It should be pointed out that given the small sample size ($N=12$), these correlations are quite substantial.

3.4 Discussion & Conclusion

Previous studies have typically used abstract stimuli like black and white geometric patterns to induce vection. Here, we show that the illusion can be enhanced if a natural scene is used instead: The current experiment 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. A possible explanation for why this happens is that natural scenes are less likely to be interpreted as moving because of the assumption of a stable environment (Dichgans & Brandt 1978).

Results from the questionnaires show that the natural, globally consistent scene was also associated with higher presence ratings than any of the sliced or scrambled stimuli. This raises the possibility that presence and vection might be directly linked. It could be the case that vection was facilitated with the natural scene stimulus because participants felt more present in it. Compatible with this hypothesis are the results from the various scrambled stimuli: neither the presence ratings nor the vection onset time or intensity showed any consistent difference in the statistical tests. Two slices/mosaics were sufficient to reduce presence and impair vection as compared to the natural scene.

In this study, the presence questionnaire showed a two-dimensional structure, namely spatial presence (factor 1) and attention/ involvement (factor 2). Furthermore, we found a differential influence of these two factors: While spatial presence was closely related to the convincingness of the rotation illusion, involvement in the simulation was more closely related to the onset time of the illusion. This 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. 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, and whether presence might also be affected by the perception of self-motion, as suggested by a recent study using the same VR setup (Riecke, Schulte-Pelkum, Avraamides, & Bülthoff, 2004): In that study, vection onset times were unexpectedly decreased when minor scratches were added to the projection screen. These hardly noticeable scratches also enhanced vection in terms of both

intensity and convincingness ratings. We are not aware of any theoretical reason why these imperfections in the simulation setup should increase presence in the simulated environment. If anything, one might rather expect a decrease in presence. Nevertheless, these minor modifications increased presence ratings significantly, which suggests that the presence increase might have been mediated by the increase in vection.

The finding that both presence and vection measures were no better for the two slices/mosaics than the 8 and 32 slices/mosaics rules out the idea that vection might be facilitated with the natural scene because it contained identifiable objects. Many scene objects could be identified with the two slices/mosaic stimuli, whereas the 8 slices/mosaics and the 32 slices/mosaics in particular contained hardly any recognizable objects. Nonetheless, no consistent improvement of vection was observed for the two slices/mosaics (apart from a small benefit in terms of convincingness ratings). That is, global scene consistency, but not the perception of individual objects seems to have determined vection and presence.

The data are, however, in full agreement with hypothesis 1: Global scene consistency played the dominant role in facilitating vection, and any global inconsistency reduced vection as well as presence and involvement considerably. Previous research has shown that adding vertical high contrast edges facilitates vection (Dichgans & Brandt 1978). It has also been found that increasing contrast and spatial frequency of a moving stimulus leads to higher perceived velocity (Distler, 2003). In our study, we found that higher rotational velocities of the stimulus induce vection more easily than slower velocities. Therefore, one would predict that the mosaics should improve vection as compared to the horizontal slices. The results of this study 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 suggests 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 higher-level 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). Higher-level factors that might have contributed include global consistency of the scene and the contained depth cues, believability of the stimulus, presence and involvement in the simulated scene, and/or the affordance (the implied possibility) of moving through the scene.

As a tentative first explanation, we propose that the globally consistent, naturalistic scene allowed for higher believability and presence in the simulated environment and thus provided observers with a more convincing, stable reference frame and primary rest 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). Even though further experiments are required to corroborate and further elucidate this phenomenon, the current experiment supports the notion that higher-level mechanisms do indeed affect the visually-induced self-motion illusion, a phenomenon that was traditionally believed to be mainly bottom-up driven. Hence, we propose that higher-level factors should be considered and further investigated both in self-motion simulation applications and in basic research – where they have been largely neglected apart from a few recent studies (Lepecq et al. 1995; Palmisano & Chan, 2004; Riecke, Schulte-Pelkum, Caniard, & Bühlhoff, 2005b). This could also be advantageous from a practical standpoint: Compared to other means of increasing the convincingness and effectiveness of self-motion simulations like increasing the visual field of view or using a motion platform, higher-level factors can often be manipulated rather easily and without much effort, such that they might be an important step towards a lean and elegant approach to effective ego-motion simulation.

4 Experiment 2: Unobtrusive modifications of projection screen can facilitate both vection and presence

Despite amazing advances in VR technology, most VR simulations still suffer from a critical problem: As soon as users are required to move about the simulated scene without sufficient landmark information, they tend to get lost quite easily, even after only a few simulated moves. This happens much more frequently than in comparable real-world situations, and provides a major challenge in VR development and basic research. Based on a theoretical framework by Riecke and von der Heyde, we propose that this lack of robust and effortless spatial orientation is at least partially caused by the lack of a convincing sensation of self-motion and spatial presence, especially when only visual cues without any physical motions are available in the virtual environment (Riecke & von der Heyde, 2002; & manuscript in preparation); von der Heyde & Riecke, 2002). Thus, it would be quite advantageous to have reliable means to increase the believability and intensity of self-motion simulations in VR without increasing simulation and financial effort unnecessarily.

The first experiment demonstrated that presenting a globally consistent, naturalistic scene already increases the self-motion sensation considerably compared to more artificial stimuli, even when the image statistics (bottom-up parameters) are relatively similar. Vection onset times were, however, still in the order of 20-30 seconds, depending on the rotational velocity. That is, most participants did not experience any self-motion until after one revolution in the virtual environment, which is unfeasible for many VR applications. Hence, from an applied perspective, there is a need for reliable methods to reduce vection onset times further (ideally approaching zero). Admittedly, it is likely that visual cues alone might not be sufficient to reliably allow for immediate vection onset, and at least some proprioceptive and/or vestibular cues might be required. Nevertheless, we propose that the need for proprioceptive and/or vestibular cues – which typically cannot be included in VR systems without considerable technical and financial effort – can be reduced to an absolute minimum if the visual VR simulation is optimized and allows already for relatively low vection onset times and compelling self-motion illusions.

So how can we further enhance visually-induced vection? It is well-known that enlarging the FOV of the moving stimulus reliably enhances vection and reduces vection onset times (Brandt, Dichgans, & Held, 1973). Full-field stimulation is known to induce most compelling self-motion sensations. Unfortunately, however, building a VR setup that offers a very wide FOV while maintaining an acceptable image resolution requires considerable technical effort and is very costly (even though costs might still be small compared to using motion platforms). So, what alternatives are there to enhance vection without increasing the simulation effort too much?

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 & Heckmann, 1989; Nakamura & Shimojo, 1999), whereas stationary objects that appear to be *behind* the moving objects tend to impair vection (Howard & Howard, 1994). Note that observers in these studies were asked to explicitly focus on and fixate those targets. From an applied or ecological perspective, such a fixation on a foreground object while moving about an environment is rather unnatural and cumbersome, though. Imagine for example being the driver of a (simulated or real) vehicle: Fixating on a foreground object could be simply done by fixating some stains on the windshield, for example. Even though this might actually increase the sensation of self-motion in a simple and cost-effective way, such behavior is both unnatural and potentially even dangerous, as fixating a foreground target typically draws attention away from the outside scene (e.g., the street to follow).

The second experiment was designed to investigate whether a minor change in the surface and reflection properties of the projection screen might have a qualitatively similar vection-facilitating effect as an explicit fixation point or foreground stimulus⁴. Note that participants in our study were asked as before to view the stimulus in a normal and relaxed manner, without trying to suppress the OKR (optokinetic reflex) by, e.g., staring or fixating as typically done in studies with fixation points. If we still find a vection-facilitating effect, this would shed a novel light on our understanding of self-motion perception. Furthermore, the ability to enhance illusory self-motion perception in a non-obtrusive way, without explicit fixation and under natural relaxed viewing conditions, would yield interesting implications for the design of lean and elegant motion simulators: From an applied perspective, one typically wants to achieve realistic ego-motion simulation *without* restricting eye movements or adding potentially disturbing foreground stimuli, ideally in a simple and unobtrusive manner. Such unobtrusive measures could be exploited in driving or flight simulators by adding for example subtle spots or dirt on the (real or simulated) windshield.

4.1 Methods

The design of the current experiment is identical to the previous experiment apart from one change: A different projection screen of identical size, material, and reflection properties was used that contained additional minor marks (scratches) in the periphery of the projection screen. Marks were located at the upper-left part of the screen, as indicated in Figure 5). The marks on the screen were not mentioned to the participants until after the experiment. In fact, only one of the participants was able to report having noticed the marks in a post-experimental interview, which illustrates the unobtrusive nature of the marks. Even if participants had noticed these marks, we believe that they would most likely have thought that those were there just accidentally and not an intended experimental manipulation.

Ten naive participants (four female) were used in the current study with the additional marks on the screen, and the data was compared to the previous experiment in a between-subject design. None of the ten participants had taken part in the previous study before.

⁴ This section is in part based on two conference presentations where a limited subset of the data has been presented (Riecke et al., 2004; Riecke et al., 2005b).

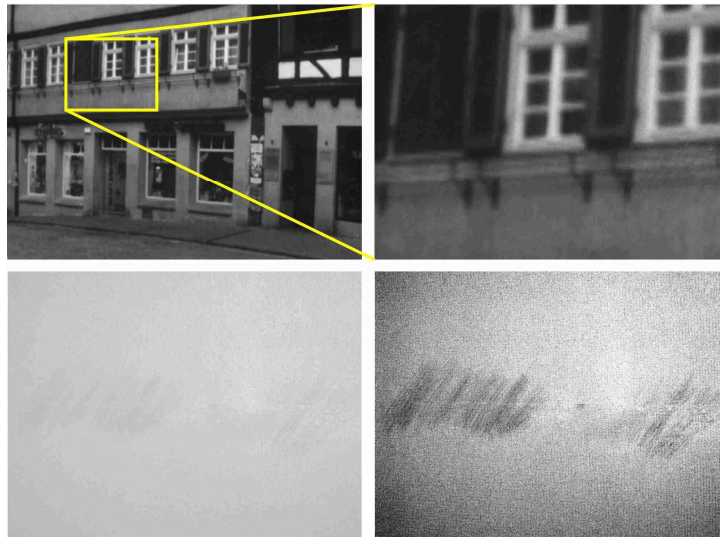


Figure 3: Top left: View of the projection screen displaying the market scene. The marks are located at the upper-left part of the screen, as illustrated by the close-ups to the right and below. Bottom: Close-up of the same region as above (right), but illuminated with plain white light to illustrate 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 & Riecke et al., 2005b (©2005 IEEE) with permission).

4.2 Results

The data for the marked screen are displayed in Figure 6, interleaved with the data from the previous experiment for easier comparability in subsection 4.2.3. Both vection onset time and convincingness ratings showed qualitatively similar results to the previous experiment: Scrambling severity and rotation velocity yielded significant effects for both vection onset time ($F(3,24)=5.18$ $p=.007$ and $F(1,8)=11.9$, $p=.009$, respectively) and convincingness ratings ($F(3,24)=8.29$ $p=.001$ and $F(1,8)=24.7$, $p=.001$, respectively). In addition, the three-way interaction between scrambling severity, session, and rotation velocity reached significance for the convincingness ratings ($F(3,24)=3.19$, $p=.042$).

Vection intensity, however, showed different results than in the previous experiment: Scrambling severity showed only a marginally significant effect ($F(3,24)=2.59$, $p=.077$). This might be due to a ceiling effect, as vection intensity was close to 100%. Furthermore, stimulus velocity and the type of scrambling (sliced vs. mosaics) reached significance ($F(1,8)=14.4$, $p=.005$ and $F(1,8)=8.01$, $p=.022$, respectively).

4.2.1 Presence Questionnaires

The results of the presence questionnaires were qualitatively similar to results from the prior experiment, as can be seen in Figure 5: The globally consistent, intact scenes showed highest presence ratings in all presence measures, and all scene scrambling reduced presence consistently. A factor analysis revealed as before a two-dimensional structure of the presence questionnaire with the factors spatial presence and involvement.

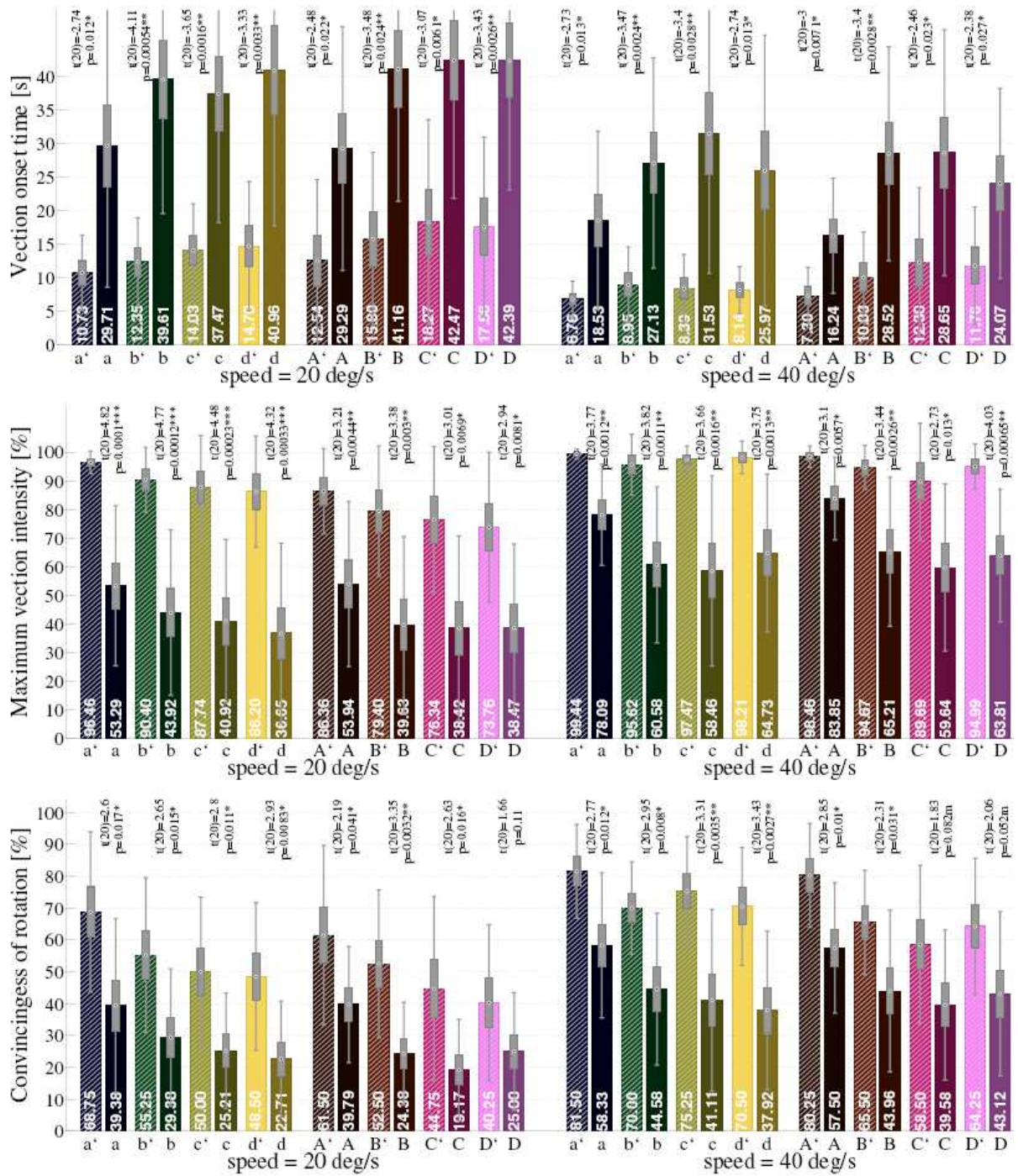


Figure 4: Mean of the three vection measures for the marked screen (hatched bars, second experiment) and clean screen (solid bars, first experiment), averaged over the ten and twelve participants, respectively. Boxes and whiskers depict one standard error of the mean and one standard deviation, respectively. The results of unpaired, two-tailed t-test are indicated at the top of each pair of bars. Note the strong vection-facilitating effect of the additional marks on the screen (hatched bars) for all measures.

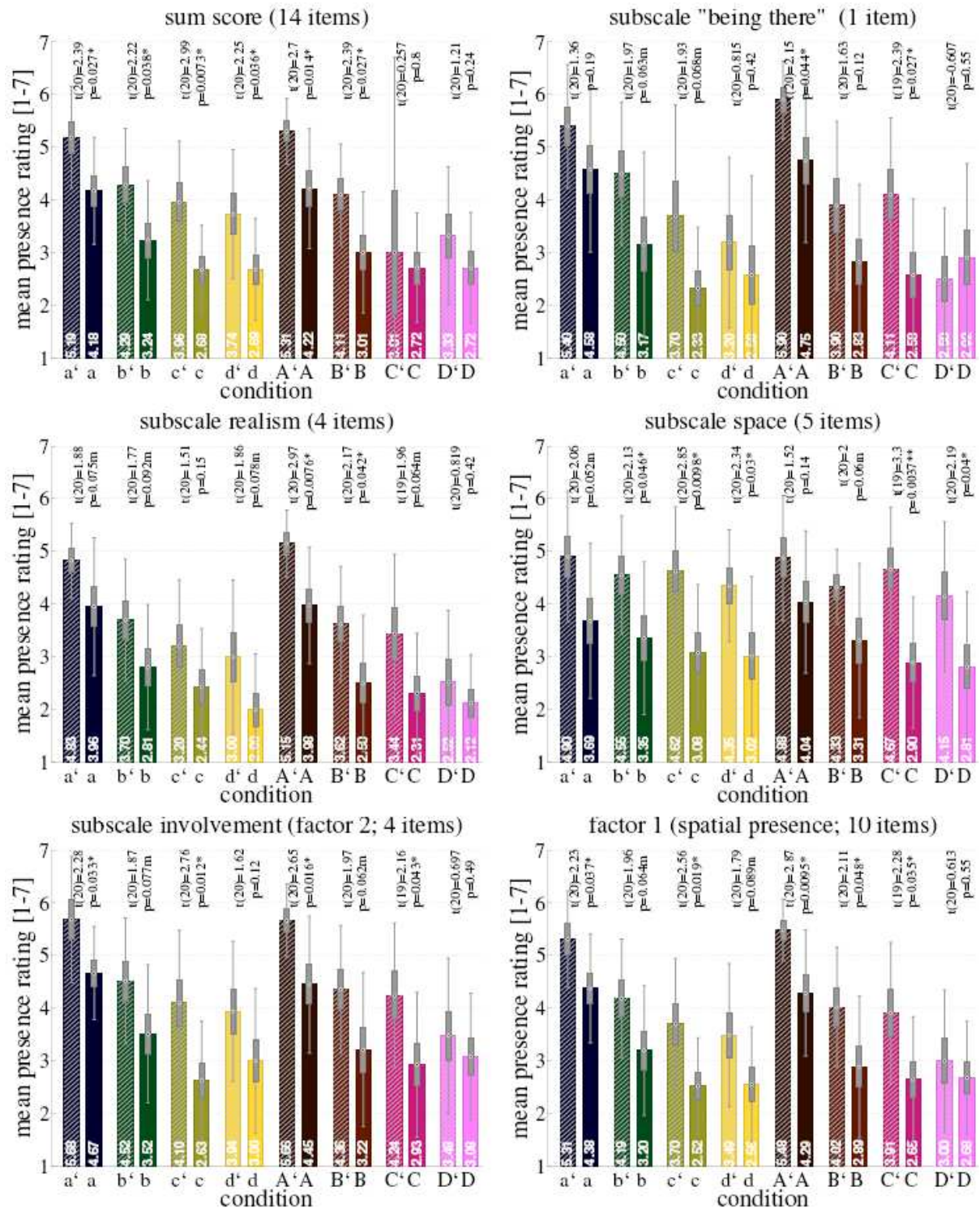


Figure 5: Mean presence ratings and sub-scales for the marked screen (hatched bars) and unmarked screen (solid bars), each plotted for the eight different visual stimuli. The top left plot shows the mean sum score over all 14 items of the Igroup Presence Questionnaire (IPQ). The following plots show the data split up according to the four original subscales as described by Schubert et al.: “Being there”, realism, space, and involvement. The two bottom plots show the mean presence ratings according to the results of the factor analysis. The involvement subscale coincides with factor 2 of the factor analysis, and the remaining 3 subscales (10 items) constitute factor 1, which can be seen as the spatial presence aspect. It can be seen that only the consistent scenes induced high spatial presence and high attentional involvement. Note the qualitatively similar pattern of results for all scales: Only the intact scenes (a, A) yielded high presence ratings, while all scene scrambling reduced presence consistently. Note also the consistently higher presence ratings for the marked screen.

4.2.2 Correlations between presence ratings and experimental measures

Results of the correlation analyses between the presence measures and the experimental data (vection onset time, convincingness, and vection intensity) are summarized in **Error! Reference source not found.** The correlations and factor analyzes reported for each of the two experiments are based on rather small sample sizes (10 and 12 observers, respectively). To ensure higher statistical power and better interpretability, the data of the 22 participants of two experiments were in addition pooled, and the same analyzes were performed as before. This is a valid method since the stimuli and procedures were exactly identical; the only difference was the presence or absence of little marks on the projection screens. The results for the pooled data are qualitatively similar to the two separate analyzes, 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 (as assessed using the IPQ), the subjective convincingness ratings which followed each trial were more tightly related to the spatial presence-related aspects of overall presence. This differential interrelation suggests a two-dimensional structure of presence with respect to ego-motion perception: Attentional aspects or involvement (e.g. awareness of real surroundings of the simulator vs. the simulated environment) on the one hand and spatial presence on the other hand.

Table 1: Paired-samples correlations for the two experiments. Correlations were computed between all three vection measures (vection onset time, convincingness, and vection intensity) and the factor values of the two factors of presence. Note the asymmetry between factor 1 “spatial presence” and factor 2 “involvement”: While factor 1 correlated only with the convincingness ratings and not with any other measures, factor 2 correlated mainly with vection onset time and vection intensity.

		factor 1 (spatial presence)			factor 2 (involvement)		
		onset time	convincingness	vection intensity	onset time	convincingness	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

4.2.3 Comparison between the unmarked and marked screen

Vection onset times were about two to three times smaller with the marked screen, as illustrated in Figure 4. Furthermore, both convincingness ratings and vection intensity were considerably higher due to the additional marks on the screen. These effects reached significance in an ANOVA that included the between-subject factor of screen type (unmarked vs. marked), all p 's $<.005$. To investigate this effect further, unpaired t-tests for the between-subject factor of screen type (unmarked vs. marked) were performed for all conditions and are indicated in Figure 4 in the top part of each plot. For both vection onset time and vection intensity, all t-tests yielded significant differences on at least a 5% level. For the convincingness ratings, only 13 out of the 16 t-tests yielded significant results.

5 Conclusions

The comparison between the marked and unmarked screen showed a considerable and highly significant vection-facilitating effect of the subtle marks on the screen for all dependent measures. 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.

It has been known that both static fixation points and static foreground stimuli can facilitate vection (Becker et al., 2002; Nakamura & Shimojo, 1999; Howard & Howard, 1994). This has been explained by increased relative motion on the retina. The novel finding from this study is that a similar effect can also occur even if the

stationary objects (or marks) or not fixated and are hardly noticeable - only one participant was able to report having noticed the marks. Notice 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 & Shimojo, 1999). Hence, these factors cannot account for the observed vection-enhancing effect.

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

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 (see Figure 6). We propose three mechanisms that might have contributed: First, adding the marks increased the relative visual between the moving stimulus and the stationary screen and marks, which might have facilitated vection. 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. 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 & Heckmann, 1989; Nakamura & Shimojo, 1999).

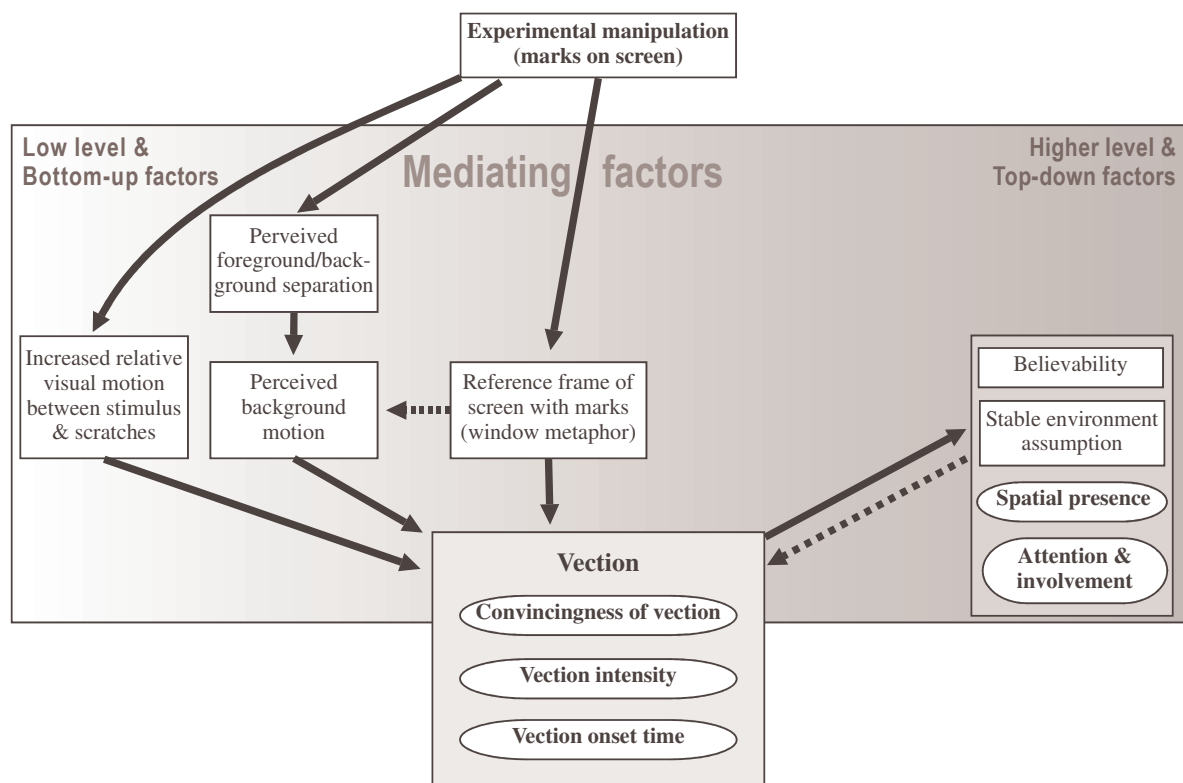


Figure 6: Schematic representation of the proposed mechanisms about how the experimental manipulation of adding marks to the screen might have affected vection and presence. Solid arrows indicate likely causal connections, whereas dashed arrows indicate more tentative lines of logic for which we do not have evidence yet. Gray-shaded items represent the items that were actually measured. Comparing 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 the visually induced self-motion illusion (vection) might have mediated or indirectly caused the observed increase in spatial presence and immersion. This hypothesis is depicted above. The marks are proposed to have facilitated vection via three potential pathways: 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 know to facilitate vection; Third, the marks provided a stable reference frame with respect to which visual motion might be more easily interpreted as self-motion than stimulus motion.

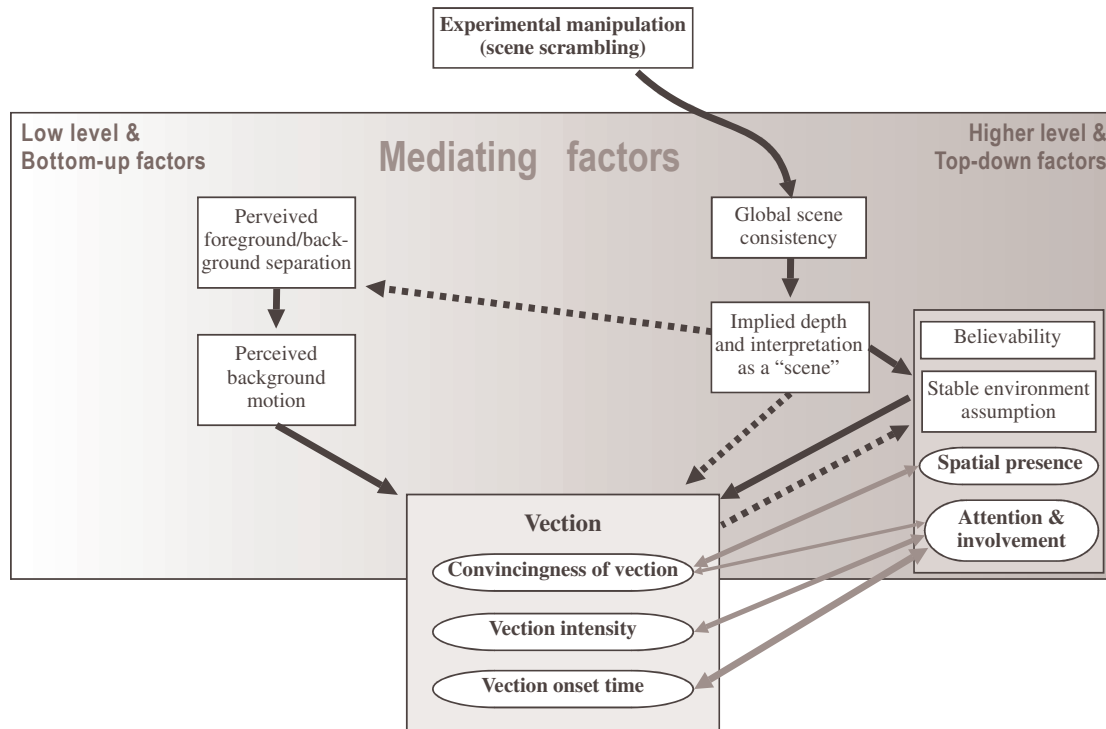


Figure 7: Results from the scene scrambling in both experiments suggest that vection might also be mediated by higher-level and/or top-down mechanism like pictorial depth cues, global scene consistency, and presence. The gray arrows depict the correlations between vection and presence measures, with the arrow thickness indicating the correlation strength.

Third, the marks might have provided some kind of subtle stationary reference frame with respect to which the moving stimulus is being perceived. A related study by Lowther and Ware demonstrated a similar vection-facilitating effect when using a stable foreground stimulus (Lowther & 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 ego-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 the 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 increases the convincingness and strength of the self-motion perception without imposing unnatural constraints on 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 (Lowther & Ware, 1996; Howard & Heckmann, 1989; Nakamura & Shimojo, 1999).

In addition to the vection-facilitating effects, the minor scratches on the screen also clearly enhanced presence, which we had not 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. 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 Figure 7.

Conversely, the comparison of the globally consistent stimulus with the scrambled, globally inconsistent stimuli (see also experiment 1) suggests that presence and involvement themselves might also be able to affect the self-motion illusion. As we argued before, the observed vection-enhancing effect of the globally consistent, naturalistic scene might have been mediated or indirectly caused by higher-level and/or top-down mechanisms like global scene consistency and the resulting consistent pictorial depth information and enhanced spatial presence and involvement. This is illustrated in previous Figure 7.

A similar mediation of vection via higher-level mechanisms like spatial presence was observed by Riecke et al. (2005c) when a globally consistent visual stimulus of a natural scene was compared to an upside-down version of the same stimulus. 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 presence and convincingness ratings 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, similar to the depiction in Figure Figure 7.

A linear vection study by Lepecq et al. (1995) provides further support for our claim that higher level processes can affect self-motion perception: Lepecq et al. demonstrated that seven year old children perceive vection earlier when they are previously shown that the chair they were seated on can physically move – even though this never happened during the actual experiment. Interestingly, this vection-facilitating influence of pre-knowledge was not present in eleven 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 adult participants were fooled into believing that they physically moved when they were previously shown that the whole experimental setup can indeed be moved physically (Schulte-Pelkum et al., 2004a; Riecke et al., 2005c). Note, however, that neither vection onset times, nor vection intensity or convincingness were significantly affected by the cognitive manipulation. In a recent study, Palmisano & Chan (2004) demonstrated that cognitive priming can also affect the time course of vection: Adult participants experienced vection earlier and the illusion lasted longer when they were seated on a potentially moving chair and were primed towards attending their 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.

Taken together, recent experiments suggest that higher-level phenomena like perceived depth structure of the stimulus, perceived foreground/background distinction (even if there is no physical separation), cognitive frameworks, ecological validity, and spatial presence and involvement are important factors that should receive more attention both in basic research and applications. These factors could be crucial especially for VR applications and self-motion simulations, as they have the potential of offering an elegant and affordable way to optimize simulations from a perceptual and effectiveness level. This is nicely demonstrated by many theme park rides, where setting up the proper cognitive framework and expectation (both highly cognitive factors) helps to draw users more easily and effectively into the simulation and into “believing”. Thus, we posit that an approach that is centred around perceptual effectiveness and not the physical realism is important both for gaining a deeper understanding in basic research and offering a lean and elegant way improve a number of applications, especially in the advancing field of virtual reality simulations. This might ultimately allow us to come closer to the fulfilling the promise of VR as a believable “window onto the simulated world”.

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