Tuning Self-Motion Perception in Virtual Reality with Visual Illusions

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Abstract—Motion perception in immersive virtual environments significantly differs from the real world. For example, previous work has shown that users tend to underestimate travel distances in virtual environments (VEs). As a solution to this problem, researchers proposed to scale the mapped virtual camera motion relative to the tracked real-world movement of a user until real and virtual motion are perceived as equal, i.e., real-world movements could be mapped with a larger gain to the VE in order to compensate for the underestimation. However, introducing discrepancies between real and virtual motion can become a problem, in particular, due to misalignments of both worlds and distorted space cognition. In this paper, we describe a different approach that introduces apparent self-motion illusions by manipulating optic flow fields during movements in VEs. These manipulations can affect self-motion perception in VEs, but omit a quantitative discrepancy between real and virtual motions. In particular, we consider to which regions of the virtual view these apparent self-motion illusions can be applied, i.e., the ground plane or peripheral vision. Therefore, we introduce four illusions and show in experiments that optic flow manipulation can significantly affect users' self-motion judgments. Furthermore, we show that with such manipulations of optic flow fields the underestimation of travel distances can be compensated.

Index Terms—Self-motion perception, virtual environments, visual illusions, optic flow.

1 Introduction

When moving through the real world, humans receive a broad variety of sensory motion cues, which are analyzed and weighted by our perceptual system [1], [2]. This process is based on multiple layers of motion detectors which can be stimulated in immersive virtual reality (VR) environments.

1.1 Motion Perception in Virtual Environments

Self-motion in VR usually differs from the physical world in terms of lower temporal resolution, latency, and other factors not present in the real world [1]. Furthermore, motion perception in immersive VEs is not veridical, but rather based on integration and weighting of often conflicting and ambiguous motion cues from the real and virtual world. Such aspects of immersive VR environments have been shown to significantly impact users' perception of distances and spatial relations in VEs, as well as self-motion perception [3], [4]. For instance, researchers often observe an under- or overestimation of travel distances or rotations [4], [5] in VEs, which is often attributed to visual self-motion perception [3]. Visual perception of self-motion in an environment is mainly related to two aspects:

- absolute landmarks, i.e., features of the environment that appear stable while a person is moving [2], and
- *optic flow*, i.e., extraction of motion cues, such as heading and speed information, from patterns formed by differences in light intensities in an optic array on the retina [6].

1.2 Manipulating Visual Motions

Various researchers focused on manipulating landmarks in immersive VEs, which do not have to be veridical as in the real world. For instance, Suma et al. [7] demonstrated that changes in position or orientation of landmarks, such as doors in an architectural model, often go unnoticed by observers when the landmark of interest was not in the observer's view during the change. These changes can also be induced if the visual information is disrupted during saccadic eye motions or a short interstimulus interval [8]. Less abrupt approaches are based on moving a virtual scene or individual landmarks relative to a user's motion [9]. For instance, Interrante et al. [10] described approaches to upscale walked distances in immersive VEs to compensate perceived underestimation of travel distances in VR. Similarly, Steinicke et al. [4] proposed up- or downscaling rotation angles to compensate observed under- or overestimation of rotations. Although such approaches can be applied to enhance self-motion judgments, and support unlimited walking through VEs when restricted to a smaller interaction space in the real world [4], the amount of manipulation that goes unnoticed by users is limited. Furthermore, manipulation of virtual motions can produce some practical issues. Since the user's physical movements do not match their motion in the VE, an introduced

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discrepancy can affect typical distance cues exploited by professionals. For instance, counting steps as distance measure is a simple approximation in the fields of architecture or urban planning, which would be distorted if the mapping between the physical and virtual motion is manipulated. Another drawback of these manipulations results from findings of Kohli et al. [11] and Bruder et al. [12] in the area of passive haptics, in which physical props, which are aligned with virtual objects, are used to provide passive haptic feedback for their virtual counterparts. In the case of manipulated mappings between real movements and virtual motions, highly complex prediction and planning is required to keep virtual objects and physical props aligned, when users intend to touch them; one reason, which hinders the use of generally applicable passive haptics.

1.3 Optic Flow Manipulations

Scaling user motion in VEs affects not only landmarks, but also changes the perceived speed of optic flow motion information. Manipulation of such optic flow cues has been considered as the contributing factor for affecting self-motion perception. However, the potential of such optic flow manipulations to induce *self-motion illusions* in VEs, e.g., via *apparent motion*, have rarely been studied in VR environments.

Apparent motion can be induced by directly stimulating the optic flow perception process, e.g., via transparent overlay of stationary scenes with 3D particle flow fields or sinus gratings [13], or by modulating local features in the visual scene, such as looped, time varying displacements of object contours [14]. Until now, the potential of affecting perceived self-motion in immersive VR environments via integration of actual as well as apparent optic flow motion sensations has not been considered.

In this paper, we extend our previous work described by Bruder et al. [15] and analyze techniques for such optic flow self-motion illusions in immersive VEs. In comparison to previous approaches these techniques neither manipulate landmarks in the VE [7] nor introduce discrepancies between real and virtual motions [4]. In psychophysical experiments, we analyze if and in how far these approaches can affect self-motion perception in VEs when applied to different regions of the visual field.

The paper is structured as follows: Section 2 presents background information on optic flow perception. Section 3 presents four different techniques for manipulation of perceived motions in immersive VEs. Section 4 describes the experiment that we conducted to analyze the potential of the described techniques. Section 5 discusses the results of the experiments. Section 6 concludes the paper and gives an overview of future work.

2 Background

2.1 Visual Motion Perception

When moving through the environment, human observers receive particular patterns of light moving over their retina. For instance, an observer walking straight ahead through a static environment sees parts of the environment gradually coming closer. Without considering semantic information, light differences seem to wander continuously outwards, originating in the point on the retina that faces in heading direction of the observer. As first observed by J.J. Gibson [6], *optic arrays* responsive to variation in light flux on the retina and *optic flow* cues, i.e., patterns originating in differences in the optic array caused by a person's self-motion, are used by the human perceptual system to estimate a person's current self-motion through the environment [16]. Two kinds of optic flow patterns are distinguished:

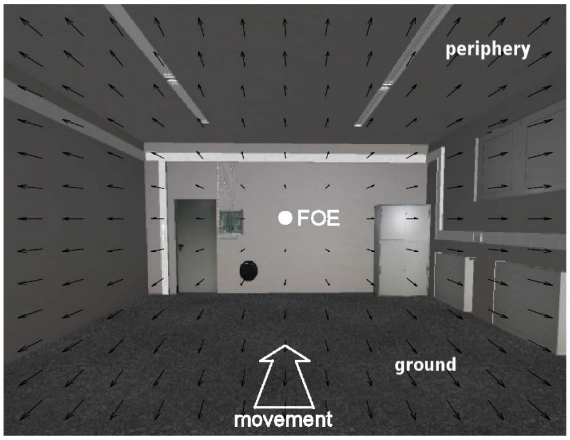


Fig. 1. Expansional optic flow patterns with FOE for translational movements, and peripheral area.

- expansional, originating from translational motions, with a point called the *focus of expansion* (FOE) in or outside the retina in current heading direction (see Fig. 1);
- directional, caused by rotational motions.

Researchers approached a better understanding of perception-action couplings related to motion perception via optic flow and extraretinal cues, and locomotion through the environment. When visual, vestibular, and proprioceptive sensory signals that normally support perception of self-motion are in conflict, optic flow can dominate extraretinal cues, which can affect perception of the momentary path and traveled distance in the environment, and can even lead to recalibration of active motor control for traveling, e.g., influencing the stride length of walkers or energy expenditure of the body [17]. Furthermore, optic flow fields that resemble motion patterns normally experienced during real self-motion can induce vection [1]. Such effects have been reported to be highly dependent on the field of view provided by the display device, and on stimulation of the peripheral regions of the observer's eyes (cf. Fig. 1), i.e., the visual system is more sensitive to self-motion information derived from peripheral regions than those derived from the foveal region [18].

In natural environments, the ground plane provides the main source for self-motion and depth information. The visual system appears to make use of this fact by showing a strong bias toward processing information that comes from the ground. For example, the ground surface is preferred as a reference frame for distance estimates: subjects use the visual contact position on the ground surface to estimate the distance of an object, although the object might also be lifted above the surface or attached to the ceiling [6], [19]. This kind of preference has been reported in various studies. On a physiological level, Portin et al. [20] found stronger cortical activation in the occipital cortex from visual stimuli in the lower visual field than from stimuli in the upper field. Marigold et al. [21] showed that obstacles on the ground can be avoided during locomotion with peripheral vision without redirecting visual fixation to the obstacles. Viewing optic flow from a textured ground plane allows accurate distance estimates which are not benefited by additional landmarks [22]. When walking on a treadmill and viewing optic flow scenes in a head-mounted display, speed estimates are more accurate when looking downward and thus experiencing more lamellar flow from the ground [23].

2.2 Visual Motion Illusions

Local velocities of light intensities in the optic array encode important information about a person's motion in the environment, but include a significant amount of noise, which has to be filtered by the perceptual system before estimating a global percept. As discussed by Hermush and Yeshurun [24], a small gap in a contour may be interpreted by the perceptual system as noise or as a significant information, i.e., the global percept is based mainly on local information, but the global percept defines whether the gap is signal or noise. The interrelation and cross-links between local and global phenomena in visual motion perception are not yet fully understood, thus models on visual perception are usually based on observations of visual motion "illusions," which are induced by customized local motion stimuli that can deceive the perceptual system into incorrect estimates of global motion [14], [25].

Over the past centuries various visual motion illusions have been described and models have been presented, which partly explain these phenomena. For example, apparent motion [13], [25] describes the perception of scene- or object motion that occurs if a stimulus is presented at discrete locations and temporally separated, i.e., not resembling a spatially and temporally continuous motion. For instance, if a sequence of two static images with local pattern displacements from image A to image B are presented in alternation [26], a viewer perceives alternating global forward and backward motion. This bidirectional motion is attributed to local motion detectors sensing forward motion during the transition $A \rightarrow B$, and backward motion $B \rightarrow A$. However, if the stimuli are customized to limited or inverse stimulation [26], [27] of motion detectors during transition $B \rightarrow A$, a viewer can perceive unidirectional, continuous motion $A \rightarrow B$.

In this paper, we consider four techniques for inducing self-motion illusions in immersive VR:

1. *Layered motion* [28], based on the observation that multiple layers of flow fields moving in different directions or with different speed can affect the global motion percept [13],
2. *Contour filtering* [14], exploiting approximations of human local feature processing in visual motion perception [25],
3. *Change blindness* [8], based on shortly blanking out the view with interstimulus intervals, potentially provoking contrast inversion of the afterimage [26], and
4. *Contrast inversion* [27], [29], based on the observation that reversing image contrast affects the output of local motion detectors.

3 Visual Self-Motion Illusions

In this section, we summarize four approaches for illusory motion in VEs and set these in relation to virtual self-motion [15].

3.1 Camera Motions in Virtual Environments

In head-tracked immersive VR environments, user movements are typically mapped one-to-one to virtual camera motions. For each frame $t \in \mathbb{N}$, the change in position and orientation measured by the tracking system is used to update the virtual camera state for rendering the new image that is presented to the user. The new camera state can be computed from the previous state defined by tuples consisting of the position $pos_{t-1} \in \mathbb{R}^3$ and orientation $(yaw_{t-1}, pitch_{t-1}, roll_{t-1}) \in \mathbb{R}^3$ in the scene with the measured change in position $\Delta pos \in \mathbb{R}^3$ and orientation $(\Delta yaw, \Delta pitch, \Delta roll) \in \mathbb{R}^3$. In the general case, we can describe a one-to-n mapping from real to virtual motions as follows:

$$pos_t = pos_{t-1} + g_T \cdot \Delta pos,$$

$$\begin{cases} yaw_t = yaw_{t-1} + g_{R[yaw]} \cdot \Delta yaw, \\ pitch_t = pitch_{t-1} + g_{R[pitch]} \cdot \Delta pitch, \\ roll_t = roll_{t-1} + g_{R[roll]} \cdot \Delta roll, \end{cases}$$

with translation gains $g_T \in \mathbb{R}$ and rotation gains $(g_{R[yaw]}, g_{R[pitch]}, g_{R[roll]}) \in \mathbb{R}^3$ [4]. As discussed by Interrante et al. [10], translation gains may be selectively applied to the main walk direction.

The user's measured self-motion and elapsed time between frame $t-1$ and frame t can be used to define relative motion via visual illusions. Two types of rendering approaches for visual illusions can be distinguished, those that are based on geometry transformations, and those that make use of screen space transformations. For the latter, self-motion through an environment produces motion patterns on the display surface similar to the optic flow patterns illustrated in Fig. 1. With simple computational models [30] such 2D optic flow vector fields can be extracted from translational and rotational motion components in a virtual 3D scene, i.e., a camera motion Δpos and $(\Delta yaw, \Delta pitch, \Delta roll)$ results in an oriented and scaled motion vector along the display surface for each pixel. Those motions can be scaled with gains $g_{T_I} \in \mathbb{R}$ and $g_{R_I} \in \mathbb{R}^3$ relative to a scene motion with $(g_{T_I} + g_T) \cdot \Delta pos$, and $(g_{R_I} + g_R) \in \mathbb{R}^3$ used to scale the yaw, pitch, and roll rotation angles. For instance, $g_{T_I} > 0$ results in an increased motion speed, whereas $g_{T_I} < 0$ results in a decreased motion speed.

3.2 Illusion Techniques

3.2.1 Layered Motion

The simplest approach to provide optic flow cues to the visual system is to display moving bars, sinus gratings, or particle flow fields with strong luminance differences to the background, for stimulation of first-order motion detectors in the visual system. In case this flow field information is presented exclusively to an observer, e.g., on a blank background, it is likely that the observer interprets this as consistent motion of the scene, whereas with multiple such

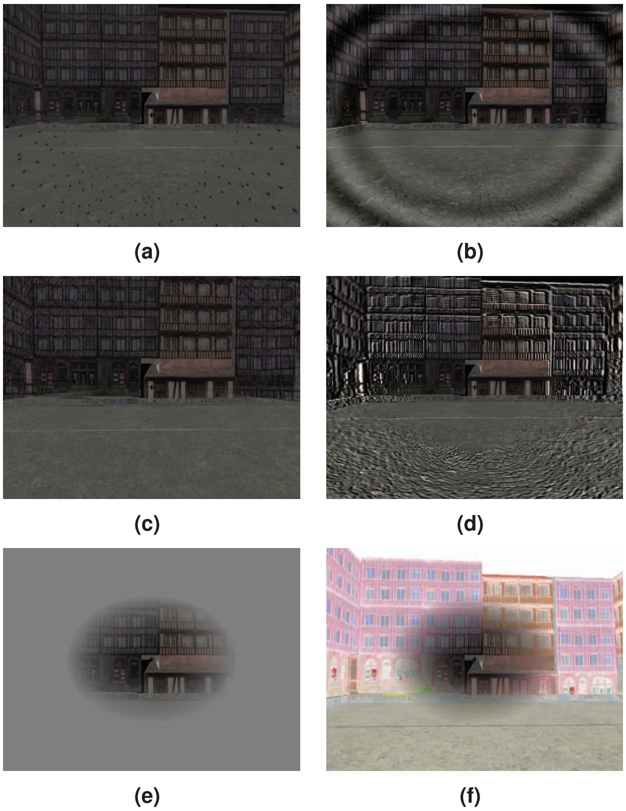


Fig. 2. Screenshots illustrating layered motion with (a) Particles, (b) sinus gratings and (c) textures fitted to the scene, as well as (d) contour filtering, (e) change blindness and (f) contrast inversion. Illusory motion stimuli are limited to peripheral regions as described in Section 3.3.1.

flow fields blended over one another, the perceptual system either interprets one of the layers as dominant scene motion, or integrates the layers to a combined global motion percept [28]. Researchers found various factors affecting this integration process, such as texture or stereoscopic depth of flow fields.

We test three kinds of simple flow fields for potential to affect the scene motion that a user perceives when walking in a realistically rendered VE. We either blend layered motion fields over the virtual scene using (T1) particle flow fields, (T2) sinus gratings [13], or (T3) motion of an infinite surface textured with a seamless tiled pattern approximating those in the virtual view (illustrated in Figs. 2a, 2b, and 2c). We steer the optic flow stimuli by modulating the visual speed and motion of the patterns relative to the user's self-motion using the 2D vector displacement that results from translational and rotational motion as described in Section 3.1. The illusion can be modulated with gains $g_{T_I} \in \mathbb{R}$ and $g_{R_I} \in \mathbb{R}^3$ applied to the translational and rotational components of one-to-one scene motion for computation of the displacement vectors.

3.2.2 Contour Filtering

Freeman et al. [14] described an illusion that is based on a pair of oriented edge filters that are applied in a convolution step to an image, which are combined using a time-dependent blending equation to form the final view. Basically, the two oriented G_2 and H_2 filters, i.e., second derivative of a Gaussian and its Hilbert transform [31], reinforce amplitude differences at luminance edges in images, and cause the edges to be slightly shifted forward or backward dependent on the orientation of the filter. The so-generated two images img_{G_2} and img_{H_2} are then blended using the frame time t as parameter for the final view via a simple equation (cf. [14]):

$$img_{G_2} \cdot cos(2\pi\, t) + img_{H_2} \cdot sin(2\pi\, t),$$

such that for the final view, each pixel's current color results as linear combination of its surrounding pixels, with weights for the surrounding pixels being continuously shifted in linear direction. Instead of using higher orders of steerable filters [14], we rotate the local 9×9 filters [31] on a per-pixel basis dependent on the pixel's simulated 2D optic flow motion direction, and scale the filter area in the convolution step using bilinear interpolation to the length of the 2D displacement vector as used for layered motion (cf. Section 3.2.1). The illusion can be modulated with gains $g_{T_I} \in \mathbb{R}$ and $g_{R_I} \in \mathbb{R}^3$ applied to the translational and rotational components of one-to-one scene motion for computation of the displacement vectors. The illusion differs significantly from layered flow fields, since the edges in the rendered view move globally with virtual camera motions, but the illusion modulates the edges to stimulate local motion detectors of the visual system [25] (illustrated in Fig. 2d).

3.2.3 Change Blindness

Change blindness describes the phenomenon that a user presented with a visual scene may fail to detect significant changes in the scene during brief visual disruptions. Although usually change blindness phenomena are studied with visual disruptions based on blanking out the screen for 60-100 ms [8], [32], changes to the scene can be synchronized with measured blinks or movements of a viewer's eyes [32], e.g., due to saccadic suppression. Assuming a rate of about four saccades and 0.2-0.25 blinks per second for a healthy observer [33], this provides the ability to change the scene roughly every 250 ms in terms of translations or rotations of the scene.

We study illusory motion based on change blindness by introducing a short-term gray screen as interstimulus interval (ISI). We manipulate the one-to-one mapping to virtual camera motions directly with gains $g_{T_I} \in \mathbb{R}$ and $g_{R_I} \in \mathbb{R}^3$, as described for translation and rotation gains in Section 3.1, i.e., we introduce an offset to the actual camera position and orientation that is accumulated since the last ISI, and is reverted to zero when the next ISI is introduced. We apply an ISI of 100 ms duration for reverse motion (see Fig. 2e). This illusion differs from the previous illusions, since it is not a screen space operation, but based on manipulations of the virtual scene, before an ISI reverts the introduced changes unnoticeably by the viewer, in particular, without stimulating visual motion detectors during reverse motion.

3.2.4 Contrast Inversion

Mather and Murdoch [27] described an illusion based on two slightly different images (plus corresponding reversed contrast images) that could induce the feeling of directional motion from the first to the second image, without stimulating visual motion detectors during reverse motion [29]. Therefore, the images A and B, as well as the contrast reversed images A^c and B^c were displayed in the following looped sequence to the viewer: $A \rightarrow B \rightarrow A^c \rightarrow B^c$. Due to the contrast reversal, motion detectors were deceived only to detect motion in the direction $A \rightarrow B$.

We study the illusion using the same manipulation of virtual camera motions with gains $g_{T_I} \in \mathbb{R}$ and $g_{R_I} \in \mathbb{R}^3$ as used for the change blindness illusion in Section 3.2.3. However, instead of applying a gray screen as ISI, we display two contrast reversed images with the same duration: $B \rightarrow A^c \rightarrow B^c \rightarrow A$, with B the last rendered image presented to the user before reverse motion, and A the image rendered after reverting the camera state to the actual camera position and orientation. This illusion is closely related to effects found during change blindness experiments, in particular, since specific ISIs can induce contrast inversion of the eye's afterimage [26]. However, since the main application of change blindness is during measured saccades, and contrast inversion stimuli require the user to see the contrast reversed images, which may be less distracting than blanking out the entire view, we study both illusions separately. Contrast reversed stimuli also appear not to be limited to the minimum display duration of 60-100 ms for change blindness stimuli [32]. An example is shown in Fig. 2f.

3.3 Blending Techniques

3.3.1 Peripheral Blending

When applying visual illusions in immersive VEs, usually these induce some kind of visual modulation, which may distract the user, in particular, if it occurs in the region of the virtual scene on which the user is focusing. To account for this aspect, we apply optic flow illusions only in the peripheral regions of the user's eyes, i.e., the regions outside the fovea that can still be stimulated with the field of view provided by the visual display device. As mentioned in Section 2, foveal vision is restricted to a small area around the optical line-of-sight. In order to provide the user with accurate vision with highest acuity in this region, we apply the described illusions only in the periphery of the user's eyes. Therefore, we apply a simple alpha blending to the display surface. We render pixels in the foveal region with the camera state defined by one-to-one or one-to-n mapping (cf. Section 3.1) and use an illusory motion algorithm only for the peripheral region. Thus, potential visual distortions do not disturb foveal information of scene objects the user is focusing on. In our studies, we ensured fixed view directions, however, a user's view direction could be measured in real time with an eye tracker, or could be predetermined by analysis of salient features in the virtual view.

3.3.2 Ground Plane Blending

As discussed in Section 2, optic flow cues can originate by movement of an observer relative to a textured ground plane. In particular, human observers can extract self-motion information by interpreting optic flow cues which are derived from the motion of the ground plane relative to the observer. These cues provide information about the walking direction, as well as velocity of the observer. In contrast to peripheral stimulation, when applying *ground plane visual illusions*, we apply visual modulations to the textured ground plane exclusively. Therefore, we apply a simple blending to the ground surface. We render pixels corresponding to objects in the scene with the camera state defined by one-to-one or one-to-n mapping (cf. Section 3.1) and use an illusory motion algorithm only for the pixels that correspond to the ground surface. As a result, we provide users with a clear view to focus objects in the visual scene, while manipulating optic flow cues that originate from the ground only. Moreover, manipulating optic flow cues from the ground plane may be applicable without the requirement for determining a user's gaze direction in real time by means of an eye tracker as discussed for peripheral stimulation.

3.4 Hypotheses

Visual illusions are usually applied assuming a stationary viewer, and have not been studied thoroughly for a moving user in an immersive VR environment. Thus, it is still largely unknown how the visual system interprets high-fidelity visual self-motion information in a textured virtual scene when exposed to illusory motion stimuli. We hypothesized that illusory motion cues can

h1. result in an integration of self-motion and illusory motion, which thus would result in the environment appearing stable, i.e., affecting perception of self-motion,

compared to the null hypothesis that the perceptual system could distinguish between self-motion and illusory motion, and interpret the illusory component as relative to the environment, thus resulting in a nonaffected percept of self-motion. Extending our previous findings that specific peripheral stimulation can affect self-motion judgments [15], we hypothesize that

h2. illusory optic flow stimulation on the ground plane can be sufficient to affect self-motion percepts.

Furthermore, if the hypotheses hold for an illusion, it is still not clear, how the self-motion percept is affected by some amount of illusory motion, for which we hypothesize that an illusory motion is not perceived to the full amount of simulated translations and rotations due to the nonlinear blending equations and stimulation of different regions of the visual field. In the following sections we address these questions.

4 Psychophysical Experiments

In this section, we describe four experiments which we conducted to analyze the presented visual illusions for potential of affecting perceived self-motion in a VE:

- Exp. E1: Layered Motion,
- Exp. E2: Contour Filtering,
- Exp. E3: Change Blindness, and
- Exp. E4: Contrast Inversion.

Therefore, we analyzed subjects' estimation of whether a physical translation was smaller or larger than a simulated virtual translation while varying the parameters of the illusion algorithms.

4.1 Experimental Design

We performed the experiments in a $10\ \mathrm{m} \times 7\ \mathrm{m}$ darkened laboratory room. The subjects wore a HMD (ProView SR80,

Fig. 3. Photo of a user during the experiments. The inset shows the visual stimulus without optic flow manipulation.

1280x1024@60 Hz, 80 degree diagonal field of view) for the stimulus presentation. On top of the HMD an infrared LED was fixed, which we tracked within the laboratory with an active optical tracking system (PPT X4 of WorldViz), which provides submillimeter precision and subcentimeter accuracy at an update rate of 60 Hz. The orientation of the HMD was tracked with a three degrees of freedom inertial orientation sensor (InertiaCube 3 of InterSense) with an update rate of 180 Hz. For visual display, system control, and logging we used an Intel computer with Core i7 processors, 6 GB of main memory and nVidia Quadro FX 4800.

In order to focus subjects on the tasks no communication between experimenter and subject was performed during the experiment. All instructions were displayed on slides in the VE, and subjects judged their perceived motions via button presses on a Nintendo Wii remote controller. The visual stimulus consisted of virtual scenes generated by Procedural's CityEngine (see Fig. 3) and rendered with the IrrLicht engine as well as our own software.

4.1.1 Materials

We instructed the subjects to walk a distance of 2 m at a reasonable speed in the real world. To the virtual translation, we applied four different translation gains g_T, i.e., identical mapping $g_T = 1.0$ of translations from the physical to the virtual world, the gain $g_T = 1.07$ at which subjects in the experiments by Steinicke et al. [4] judged physical and virtual motions as equal, as well as the thresholds $g_T = 0.86$ and $g_T = 1.26$ at which subjects could just detect a discrepancy between physical and virtual motions. For all translation gains, we tested parameters g_{T_I} between -1.0 and 1.0 in steps of $0.\overline{3}$ for illusory motion as described in Section 3.1. We randomized the independent variables over all trials, and tested each four times.

At the beginning of each trial, the virtual scene was presented on the HMD together with the written instruction to focus the eyes on a small crosshair drawn at eye height, and walk forward until the crosshair turned red. The crosshair ensured that subjects looked at the center of the peripheral blending area described in Section 3.3.1. In the experiment, we tested the effects of peripheral blending and ground plane blending on self-motion judgments. Subjects indicated the end of the walk with a button press on the Wii controller (see Fig. 3). Afterward, the subjects had to decide whether the simulated virtual translation was smaller (down button) or larger (up button) than the physical translation. Subjects were guided back to the start position via two markers on a white screen.

4.1.2 Participants

The experiments were performed in two blocks. We applied peripheral blending in the trials for the first block, whereas ground plane blending was applied for the second block.

Eight male and two female (age 26-31, $\varnothing : 27.7$) subjects participated in the experiment, for which we applied peripheral blending (cf. [15]). Three subjects had no game experience, one had some, and six had a lot of game experience. Eight of the subjects had experience with walking in a HMD setup. All subjects were naïve to the experimental conditions.

Fourteen male and two female (age 21-31, $\varnothing : 26.6$) subjects participated in the experiment, for which we applied ground plane blending. Two subjects had no game experience, four had some, and ten had much game experience. Twelve of the subjects had experience with walking in a HMD setup. Six subjects participated in both blocks.

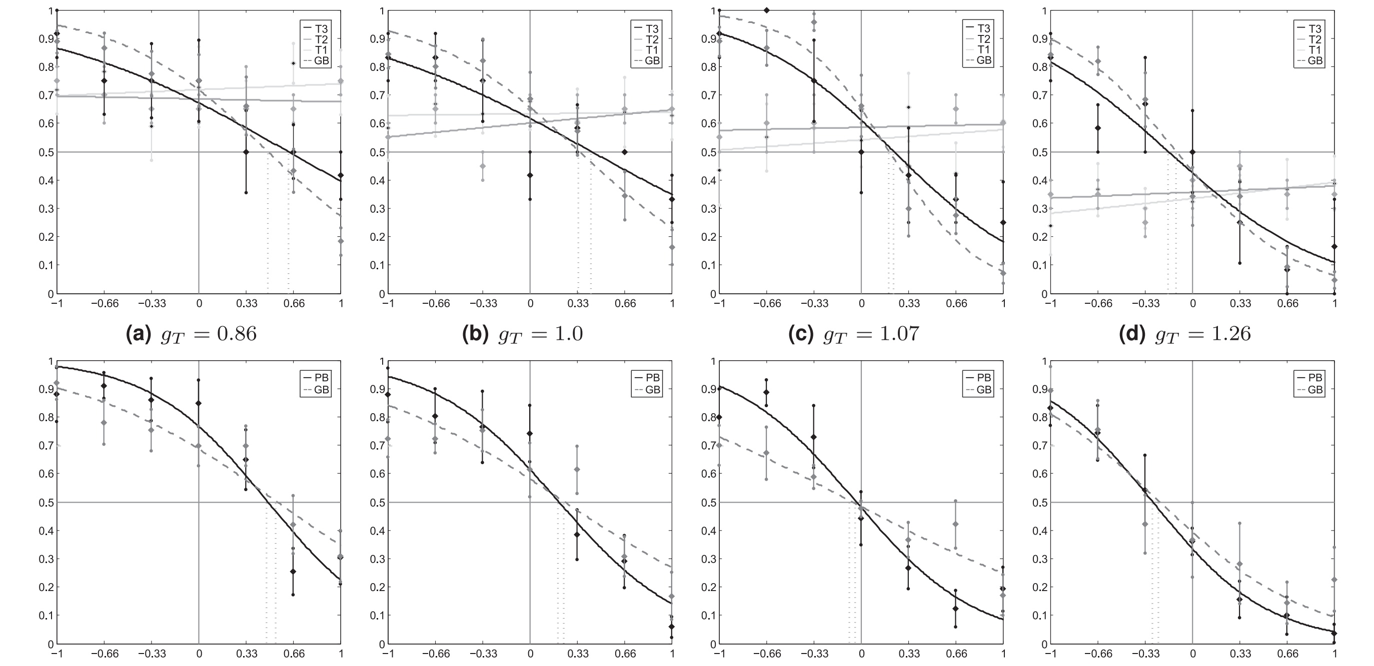
The total time per subject including prequestionnaire, instructions, training, experiments, breaks, and debriefing was 3 hours for both blocks. Subjects were allowed to take breaks at any time. All subjects were students of computer science, mathematics, or psychology. All had normal or corrected to normal vision.

4.1.3 Methods

For the experiments we used a within subject design, with the method of constant stimuli in a *two-alternative forced-choice* (2AFC) task [34]. In the method of constant stimuli, the applied gains are not related from one trial to the next, but presented randomly and uniformly distributed. To judge the stimulus in each trial, the subject has to choose between one of two possible responses, e.g., "Was the virtual movement *smaller* or *larger* than the physical movement?" When the subject cannot detect the signal, the subject must guess, and will be correct on average in 50 percent of the trials.

The gain at which the subject responds "smaller" in half of the trials is taken as the *point of subjective equality* (PSE), at which the subject judges the physical and the virtual movement as identical. As the gain decreases or increases from this value the ability of the subject to detect the difference between physical and virtual movement increases, resulting in a psychometric curve for the discrimination performance. The discrimination performance pooled over all subjects is usually represented via a psychometric function of the form $f(x) = \frac{1}{1+e^{a \cdot x+b}}$ with fitted real numbers a and b [34]. The PSEs give indications about how to parametrize the illusion such that virtual motions appear natural to users.

We measured an impact of the illusions on the subjects' sense of presence with the SUS questionnaire [35], and simulator sickness with Kennedy's SSQ [36] before and after each experiment. In addition, we asked subjects to judge



(a) $g_T = 0.86$ (b) $g_T = 1.0$ (c) $g_T = 1.07$ (d) $g_T = 1.26$

(e) $g_T = 0.86$ (f) $g_T = 1.0$ (g) $g_T = 1.07$ (h) $g_T = 1.26$

Fig. 4. Pooled results of the discrimination between virtual and physical translations. The x-axis shows the applied parameter g_{T_I}. The y-axis shows the probability of estimating the virtual motion as smaller than the physical motion. The plots (a)-(d) show results from experiment E1 for the tested translation gains, (e)-(h) show the results from experiment E2.

and compare the illusions via 10 general usability questions on visual quality, noticeability, and distraction. Materials and methods were equal for all four conducted experiments. The order of the experiments was randomized.

4.2 Experiment E1: Layered Motion

We analyzed the impact of the three layered motion techniques T1, T2, and T3 described in Section 3.2.1 with independent variable g_{T_I} on self-motion perception, and applied peripheral blending as described in Section 3.3.1. Moreover, we tested technique T3 with the ground plane blending (GB) approach described in Section 3.3.2.

4.2.1 Results

Figs. 4a, 4b, 4c, and 4d show the pooled results for the gains $g_T \in \{0.86, 1.0, 1.07, 1.26\}$ with the standard error over all subjects. The x-axis shows the parameter $g_{T_I} \in \{-1, -0.\overline{6}, -0.\overline{3}, 0, 0.\overline{3}, 0.\overline{6}, 1\}$, the y-axis shows the probability for estimating a physical translation as larger than the virtual translation. The light-gray psychometric function shows the results for technique T1, the mid-gray function for technique T2, and the black function for technique T3 applied with peripheral blending. From the psychometric functions for technique T3 we determined PSEs at $g_{T_I} = 0.6325$ for $g_T = 0.86$, $g_{T_I} = 0.4361$ for $g_T = 1.0$, $g_{T_I} = 0.2329$ for $g_T = 1.07$, and $g_{T_I} = -0.1678$ for $g_T = 1.26$. The dashed dark-gray psychometric function shows the results for technique T3 applied with ground plane blending, for which we determined PSEs at $g_{T_I} = 0.4859$ for $g_T = 0.86$, $g_{T_I} = 0.3428$ for $g_T = 1.0$, $g_{T_I} = 0.1970$ for $g_T = 1.07$, and $g_{T_I} = -0.1137$ for $g_T = 1.26$.

4.2.2 Discussion

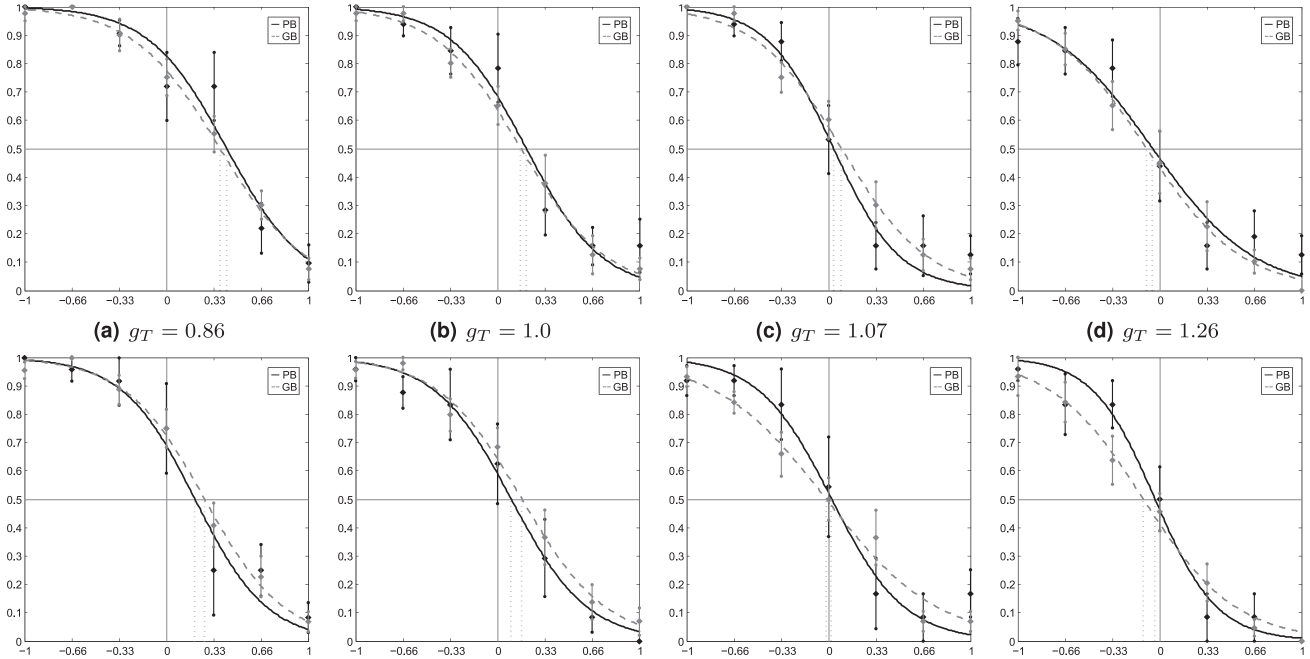
For $g_{T_I} = 0$ the results for the three techniques and four tested translation gains approximate results found by Steinicke et al. [4], i.e., subjects slightly underestimated translations in the VE in case of a one-to-one mapping. The results plotted in Figs. 4a, 4b, 4c, and 4d show a significant impact of parameter g_{T_I} on motion perception only for technique T3. Techniques T1 and T2 had no significant impact on subjects' judgment of travel distances, i.e., motion cues induced by the rendering techniques could be interpreted by the visual system as external motion in the scene, rather than self-motion. As suggested by Johnston et al. [37] this result may be explained by the interpretation of the visual system of multiple layers of motion information, in particular due to the dominance of second-order motion information such as translations in a textured scene, which may be affected by the textured motion layer in technique T3. Both peripheral blending and ground plane blending sufficed to affect the subjects' self-motion judgments.

4.3 Experiment E2: Contour Filtering

We analyzed the impact of the contour filtering illusion described in Section 3.2.2 with independent variable g_{T_I} on self-motion perception, and applied peripheral blending (PB) as described in Section 3.3.1, and ground plane blending (GB) as described in Section 3.3.2.

4.3.1 Results

Figs. 4e, 4f, 4g, and 4h show the pooled results for the four tested gains $g_T \in \{0.86, 1.0, 1.07, 1.26\}$ with the standard error over all subjects for the tested parameters $g_{T_I} \in \{-1, -0.\overline{6}, -0.\overline{3}, 0, 0.\overline{3}, 0.\overline{6}, 1\}$. The x-axis shows the parameter g_{T_I}, the y-axis shows the probability for estimating a physical translation as larger than the virtual translation. The solid psychometric function shows the results of peripheral blending, and the dashed function the results of ground



(a) $g_T = 0.86$ (b) $g_T = 1.0$ (c) $g_T = 1.07$ (d) $g_T = 1.26$

(e) $g_T = 0.86$ (f) $g_T = 1.0$ (g) $g_T = 1.07$ (h) $g_T = 1.26$

Fig. 5. Pooled results of the discrimination between virtual and physical translations. The x-axis shows the applied parameter g_{T_I}. The y-axis shows the probability of estimating the virtual motion as smaller than the physical motion. The plots (a)-(d) show results from experiment E3 for the tested translation gains, (e)-(h) show the results from experiment E4.

plane blending. From the psychometric functions for peripheral blending, we determined PSEs at $g_{T_I} = 0.4844$ for $g_T = 0.86$, $g_{T_I} = 0.2033$ for $g_T = 1.0$, $g_{T_I} = -0.0398$ for $g_T = 1.07$, and $g_{T_I} = -0.2777$ for $g_T = 1.26$. For ground plane blending, we determined PSEs at $g_{T_I} = 0.5473$ for $g_T = 0.86$, $g_{T_I} = 0.2428$ for $g_T = 1.0$, $g_{T_I} = -0.0775$ for $g_T = 1.07$, and $g_{T_I} = -0.2384$ for $g_T = 1.26$.

4.3.2 Discussion

Similar to the results found in experiment E1 (cf. Section 4.2), for $g_{T_I} = 0$ the results for the four tested translation gains approximate results found by Steinicke et al. [4]. For all translation gains, the results plotted in Figs. 4e, 4f, 4g, and 4h show a significant impact of parameter g_{T_I} on motion perception, with a higher probability for estimating a larger virtual translation if a larger parameter is applied and vice versa. The results show that the illusion can successfully impact subjects' judgments of travel distances by increasing or decreasing the motion speed via transformation of local features in the periphery, or on the ground.

For peripheral blending, the PSEs show that for a translation speed of $+48\%$ in the periphery in case of a -14% decreased motion speed in the fovea ($g_T = 0.86$) subjects judged real and virtual translations as identical, with $+20\%$ for one-to-one mapping ($g_T = 1.0$), -4% for $+7\%$ ($g_T = 1.07$), and -28% for $+26\%$ ($g_T = 1.26$). For ground plane blending, the PSEs show that for a translation speed of $+55\%$ in relation to the ground in case of a -14% decreased motion speed in the scene ($g_T = 0.86$) subjects judged real and virtual translations as identical, with $+24\%$ for one-to-one mapping ($g_T = 1.0$), -8% for $+7\%$ ($g_T = 1.07$), and -24% for $+26\%$ ($g_T = 1.26$). The PSEs motivate that applying illusory motion via the local contour filtering approach can make translation distance judgments match walked distances.

4.4 Experiment E3: Change Blindness

We analyzed the impact of change blindness (see Section 3.2.3) with independent variable g_{T_I} on self-motion perception, and applied peripheral blending as described in Section 3.3.1, and ground plane blending as described in Section 3.3.2.

4.4.1 Results

Figs. 5a, 5b, 5c, and 5d show the pooled results for the four tested gains $g_T \in \{0.86, 1.0, 1.07, 1.26\}$ with the standard error over all subjects for the tested parameters $g_{T_I} \in \{-1, -0.\overline{6}, -0.\overline{3}, 0, 0.\overline{3}, 0.\overline{6}, 1\}$. The x-axis shows the parameter g_{T_I}, the y-axis shows the probability for estimating a physical translation as larger than the virtual translation. The solid psychometric function shows the results of peripheral blending, and the dashed function the results of ground plane blending. From the psychometric functions for peripheral blending, we determined PSEs at $g_{T_I} = 0.4236$ for $g_T = 0.86$, $g_{T_I} = 0.2015$ for $g_T = 1.0$, $g_{T_I} = 0.0372$ for $g_T = 1.07$, and $g_{T_I} = -0.0485$ for $g_T = 1.26$. For ground plane blending, we determined PSEs at $g_{T_I} = 0.3756$ for $g_T = 0.86$, $g_{T_I} = 0.1635$ for $g_T = 1.0$, $g_{T_I} = 0.0924$ for $g_T = 1.07$, and $g_{T_I} = -0.0906$ for $g_T = 1.26$.

4.4.2 Discussion

In case no illusory motion was applied with $g_{T_I} = 0$ the results for the four tested translation gains approximate results found by Steinicke et al. [4]. For all translation gains, the results plotted in Figs. 5a, 5b, 5c, and 5d show a significant impact of parameter g_{T_I} on motion perception, with a higher probability for estimating a larger virtual translation if a larger parameter is applied and vice versa. The results show that the illusion can successfully impact subjects' judgments of travel distances by increasing or decreasing the motion speed in the periphery, or on the ground.

For peripheral blending, the PSEs show that for a translation speed of $+42\%$ in the periphery in case of a -14% decreased motion speed in the fovea ($g_T = 0.86$) subjects judged real and virtual translations as identical, with $+20\%$ for one-to-one mapping ($g_T = 1.0$), $+3\%$ for $+7\%$ ($g_T = 1.07$), and -5% for $+26\%$ ($g_T = 1.26$). The results illustrate that foveal and peripheral motion cues are integrated, rather than dominated exclusively by foveal or peripheral information. For ground plane blending, the PSEs show that for a translation speed of $+38\%$ in relation to the ground in case of a -14% decreased motion speed in the scene ($g_T = 0.86$) subjects judged real and virtual translations as identical, with $+16\%$ for one-to-one mapping ($g_T = 1.0$), $+9\%$ for $+7\%$ ($g_T = 1.07$), and -9% for $+26\%$ ($g_T = 1.26$). The PSEs motivate that applying illusory motion via the change blindness approach can make translation distance judgments match walked distances, i.e., it can successfully be applied to enhance judgment of perceived translations in case of a one-to-one mapping, as well as compensate for perceptual differences introduced by scaled walking [10].

4.5 Experiment E4: Contrast Inversion

We analyzed the impact of contrast inversion (see Section 3.2.4) with independent variable g_{T_I} on self-motion perception, and applied peripheral blending as described in Section 3.3.1, and ground plane blending as described in Section 3.3.2.

4.5.1 Results

Figs. 5e, 5f, 5g, and 5h show the pooled results for the gains $g_T \in \{0.86, 1.0, 1.07, 1.26\}$ with the standard error over all subjects. The x-axis shows the parameter $g_{T_I} \in \{-1, -0.\overline{6}, -0.\overline{3}, 0, 0.\overline{3}, 0.\overline{6}, 1\}$, the y-axis shows the probability for estimating a physical translation as larger than the virtual translation. The solid psychometric function shows the results of peripheral blending, and the dashed function the results of ground plane blending. From the psychometric functions, for peripheral blending we determined PSEs at $g_{T_I} = 0.2047$ for $g_T = 0.86$, $g_{T_I} = 0.0991$ for $g_T = 1.0$, $g_{T_I} = 0.0234$ for $g_T = 1.07$, and $g_{T_I} = -0.0315$ for $g_T = 1.26$. For ground plane blending, we determined PSEs at $g_{T_I} = 0.2730$ for $g_T = 0.86$, $g_{T_I} = 0.1736$ for $g_T = 1.0$, $g_{T_I} = -0.0144$ for $g_T = 1.07$, and $g_{T_I} = -0.1144$ for $g_T = 1.26$.

4.5.2 Discussion

Similar to the results found in experiment E3 (cf. Section 4.4), for $g_{T_I} = 0$ the results for the four tested translation gains approximate results found by Steinicke et al. [4], and the results plotted in Figs. 5e, 5f, 5g, and 5h show a significant impact of parameter g_{T_I} on motion perception, resulting in a higher probability for estimating a larger virtual translation if a larger parameter is applied and vice versa. The results show that the contrast inversion illusion can successfully impact subjects' judgments of travel distances by increasing or decreasing the motion speed in the periphery, or on the ground.

For peripheral blending, the PSEs show that for a translation speed of $+21\%$ in the periphery in case of a -14% decreased motion speed in the fovea ($g_T = 0.86$) subjects judged real and virtual translations as identical, with $+10\%$ for one-to-one mapping ($g_T = 1.0$), $+2\%$ for $+7\%$ ($g_T = 1.07$), and -3% for $+26\%$ ($g_T = 1.26$). For ground plane blending, the PSEs show that for a translation speed of $+27\%$ in relation to the ground in case of a -14% decreased motion speed in the scene ($g_T = 0.86$) subjects judged real and virtual translations as identical, with $+17\%$ for one-to-one mapping ($g_T = 1.0$), -1% for $+7\%$ ($g_T = 1.07$), and -11% for $+26\%$ ($g_T = 1.26$). The results match in quality results found in experiment E3, but differ in quantity of applied parameters g_{T_I}, which may be due to the currently still largely unknown reactions of the visual system to interstimulus intervals via gray screens, and reversal of contrast.

5 General Discussion

In the four experiments, we analyzed subjects' judgments of self-motions, and showed that the illusions' steering parameter g_{T_I} significantly affected the results in experiments E2 to E4, but only affected results for technique T3 in experiment E1. The results support both hypothesis h1 and h2 in Section 3.4. Furthermore, we showed with experiment E1 that it is not sufficient to overlay scene motion with any kind of flow information, e.g., particles or sinus gratings, to affect self-motion perception in immersive VEs, but rather require the layered motion stimulus to mirror the look of the scene. Experiment E2 motivates that introducing faster or slower local contour motion in the view can affect the global self-motion percept, though it is not fully understood how global and local contour motion in a virtual scene are integrated by the perceptual system. Experiments E3 and E4 show that with short change blindness ISIs or contrast reversed image sequences, a different visual motion speed can be presented to subjects while maintaining a controllable maximal offset to one-to-one or one-to-n mapped virtual camera motion, i.e., displacements due to scaled walking can be kept to a minimum.

The PSEs give indications about how to apply these illusions to make users' judgments of self-motions in immersive VEs match their movements in the real world. For a one-to-one mapping of physical user movements subjects underestimated their virtual self-motion in all experiments. Slightly increased illusory optic flow cues cause subjects to perceive the virtual motion as matching their real-world movements, an effect that otherwise required upscaling of virtual translations with a gain of about $g_T = 1.07$ (see Section 4.1.1), causing a mismatch between the real and virtual world. For the detection thresholds $g_T = 0.86$ and $g_T = 1.26$ determined by Steinicke et al. [4], at which subjects could just detect a manipulation of virtual motions, we showed that corresponding PSEs for illusory motion cues can compensate for the up- or downscaled scene motion. In this case, subjects estimated virtual motions as matching their real movements. The results motivate that illusory motion can be applied to increase the range of unnoticeable scaled walking gains.

Different stimulation of motion detectors in the subjects' periphery than in the foveal center region proved applicable in the experiments. Informal posttests without peripheral blending in experiment E1 revealed that this was not the main cause for unaffected motion percepts for techniques T1 and T2. In particular, experiments E3 and E4 revealed a dominance of peripheral motion information compared to foveal motion cues. However, it is still largely unknown how the perceptual system resolves cue conflicts as induced by peripheral stimulation with the described illusions.

Applying illusory motion only to the ground plane led to qualitatively similar results. Differences were most observable in the case of contour filtering. The filtering in that case might have been less effective because contours on the ground plane were not that sharp in the visual stimuli of the experiment. However, the resulting PSEs are almost exactly the same. This offers the opportunity to apply the presented illusions only to the ground plane with less distraction in the visual field and without the requirement for determining the user's gaze direction. Given the fact that a crucial part of the ground plane was not visible due to limitations of the field of view, using a display with a larger vertical view might even further enhance the effect of manipulating the ground plane.

Before and after the experiments, we asked subjects to judge their level of simulator sickness and sense of presence (cf. Section 4.1.3), and compare the illusions by judging differences in visual quality and related factors in 10 questions. For simulator sickness, we have not found significant differences between the four experiments, with an average increase of mean SSQ-scores of 8.6 for the peripheral blending trials, and 9.1 for ground plane blending, which is in line with previous results when using HMDs over the time of the experiment. We have not found a significant impact of the illusions on the mean SUS presence scores, with an average SUS-score of 4.2 for the peripheral blending trials, and 4.3 for ground plane blending, which reflects low, but typical results. Subjects estimated the difficulty of the task on a 5-point Likert-scale (0 very easy, 4 very difficult) with 3.1 (T1), 2.8 (T2), 1.8 (T3) in E1, 1.5 in E2, 0.3 in E3, and 0.4 in E4 for the peripheral blending trials. For the ground plane blending, trials subjects estimated the difficulty of the task with 2.8 in E1, 2.8 in E2, 0.5 in E3, and 0.8 in E4. On comparable Likert-scales subjects estimated perceived cues about their position in the laboratory during the experiments due to audio cues as 0.5 and visual cues as 0.0. Via the informal usability questions most subjects judged visual quality as most degraded in experiment E1, followed by E2, E4, and E3 when we applied peripheral blending. For ground plane blending, subjects responded with E2, E1, E4, and E3, respectively. Subjects judged that visual modifications induced in all illusions could be noticed, however, subjects estimated that only layered motion and contour filtering had potential for distracting a user from a virtual task. Moreover, one subject remarked:

> *"The illusion on the ground was much less distracting than in the entire periphery-to the point where it was barely noticeable."*

This was a typical comment of subjects who participated in both experiment blocks with peripheral and ground plane stimulation.

6 Conclusion and Future Work

In this paper, we presented four visual self-motion illusions for immersive VR environments, and evaluated the illusions in different regions of the visual field provided to users. In a psychophysical experiment, we showed that the illusions can affect travel distance judgments in VEs. In particular, we showed that the underestimation of travel distances observed in case of a one-to-one mapping from real to virtual motions of a user can be compensated by applying illusory motion with the PSEs determined in the experiments. We also evaluated potential of the presented illusions for enhancing applicability of scaled walking by countering the increased or decreased virtual traveling speed of a user by induced illusory motion. Our results show that for changed PSEs subjects judged such real and virtual motions as equal, which illustrates the potential of visual illusions to be applied in case virtual motions have to be manipulated with scaled walking gains that otherwise would be detected by users. Moreover, we found that illusory motion stimuli can be limited to peripheral regions or the ground plane only, which limits visual artifacts and distraction of users in immersive VR environments.

In the future, we will pursue research in the direction of visual illusions that are less detectable by users, but still effective in modulating perceived motions. More research is needed to understand why space perception differs in immersive VR environments from the real world, and how space perception is affected by manipulation of virtual translations and rotations.

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