Exploiting Perceptual Limitations and Illusions to Support Walking through Virtual Environments in Confined Physical Spaces

Gerd Bruder[a,*], Frank Steinicke[a], Benjamin Bolte[b], Phil Wieland[b], Harald Frenz[b],
Markus Lappe[b,c]

[a]*Institute of Computer Science & Institute of Human-Computer-Media*
University of Würzburg, Germany
[b]*Institute of Psychology*
University of Münster, Germany
[c]*Otto Creutzfeldt Center for Cognitive and Behavioral Neuroscience*
University of Münster, Germany

Abstract

Head-mounted displays (HMDs) allow users to immerse in a virtual environment (VE) in which the user's viewpoint can be changed according to the tracked movements in real space. Because the size of the virtual world often differs from the size of the tracked lab space, a straightforward implementation of omni-directional and unlimited walking is not generally possible. In this article we review and discuss a set of techniques that use known perceptual limitations and illusions to support seemingly natural walking through a large virtual environment in a confined lab space. The concept behind these techniques is called *redirected walking*. With redirected walking, users are guided unnoticeably on a physical path that differs from the path the user perceives in the virtual world by

---

[*] Tel. +49 931 31 85868 / Fax +49 931 31 87364
Email address: `gerd.bruder@uni-wuerzburg.de` (Gerd Bruder)
URL: `http://img.uni-wuerzburg.de/personen/dr_gerd_bruder/` (Gerd Bruder)

Preprint submitted to Display *March 12, 2013*

manipulating the transformations from real to virtual movements. For example, virtually rotating the view in the HMD to one side with every step causes the user to unknowingly compensate by walking a circular arc in the opposite direction, while having the illusion of walking on a straight trajectory. We describe a number of perceptual illusions that exploit perceptual limitations of motion detectors to manipulate the user's perception of the speed and direction of his motion. We describe how gains of locomotor speed, rotation, and curvature can gradually alter the physical trajectory without the users observing any discrepancy, and discuss studies that investigated perceptual thresholds for these manipulations. We discuss the potential of self-motion illusions to shift or widen the applicable ranges for gain manipulations and to compensate for over- or underestimations of speed or travel distance in VEs. Finally, we identify a number of key issues for future research on this topic.

Keywords: perception, virtual reality, immersive virtual environment

---

1. Locomotion in Virtual Environments

In the real world we navigate with ease by walking, running, driving etc. Sensory information such as vestibular, proprioceptive, and efferent copy signals as well as visual information create consistent multi-sensory cues that indicate one's own acceleration, speed and direction of travel. Since walking is the most basic and intuitive way of moving within the real world, keeping such an active and dynamic ability to navigate through large-scale virtual environments (VEs) is highly desirable for many 3D applications, such as urban planning, tourism, 3D entertainment, serious games, robotics etc. Although these application domains are inherently three-dimensional, usually virtual reality (VR)-based user interfaces do not support real full-scale walking [1].

Immersive VEs were initially restricted to visual displays, combined with interaction devices for providing (often unnatural) inputs (e. g., a joystick or mouse) to generate self-motion. More and more research groups are investigating natural, multimodal methods of generating self-motion. Typically, immersive VEs are characterized, for example, by head-mounted displays (HMDs) and a tracking system for measuring position and orientation data.

An obvious approach to implement real walking in such a setup is to map the user's head movements or gaits to changes of the virtual camera by means of a one-to-one mapping. This technique has the drawback that the user's movements are restricted by the limited range of the tracking sensors and a rather small tracked lab space in the real word. Therefore, the first challenge for virtual locomotion interfaces is that they enable walking over large distances in the virtual world while physically remaining within a reasonably small space.

To address unlimited walking in immersive VEs, various prototypes of interface devices have been developed to prevent a displacement in the real world. These devices include torus-shaped omni-directional treadmills [2, 3, 4], motion foot pads, robot tiles [5, 6] and motion carpets [7]. All these systems are costly and support only a single user. For multi-walker scenarios it would be necessary to equip each user with a separate device therefore increasing the costs enormously. Although these hardware systems represent distinctive technological achievements, most likely they will not be generally available in the foreseeable future due to the described limitations. Hence there is a demand for alternative, more cost-effective and practical approaches. As a solution to this challenge, traveling by exploiting walk-like gestures has been proposed in several scenarios that give the user the impression of walking. For example, the walking-in-place approach exploits walk-like gestures to travel through a VE, while the user stays physically at almost the same position [8, 9]. However, real walking has been shown to be a more presence-enhancing and natural locomotion technique than any of these navigation metaphors [9, 10].

1.1. Natural Locomotion and Redirected Walking

As an alternative to the technological achievements in locomotion hardware devices, a counter-movement has gained a foothold in the VR community for supporting unrestricted real walking. *Redirected walking* denotes approaches in immersive VEs that do not rely on locomotion hardware, but which are inspired by findings from the field of psychology. The goal of redirected walking is to break the limitations imposed by the tracking space in the physical world, and provide users with the ability to explore an arbitrarily-sized VE. Therefore, several techniques with different strengths and weaknesses implement redirected walking: *Repositioning techniques* redirect the user by manipulating the correspondence between points in the physical and virtual world to compress a larger virtual space into a smaller physical workspace [11, 12]. *Reorientation techniques*, on the other hand, attempt to inconspicuously rotate the user's heading away from obstacles or the boundaries of the physical workspace [13]. *Change blindness techniques* redirect the user by manipulating the scene geometry, for instance, changing the position of a door to guide him in the physical world, e. g., preventing him from leaving the tracked lab space [14, 15, 16]. Some of these redirection techniques are designed to be *overt* to users, i. e., the user is aware of the manipulation. *Subtle* redirection techniques, in contrast, avoid that users notice the manipulation. In this article we focus on subtle redirection techniques.

With subtle redirected walking the user is redirected in the real world via perceptually undetectable manipulations applied to the displayed scene, causing users to unknowingly compensate by repositioning or reorienting themselves [17]. In Figure 1 the concept of redirected walking is illustrated; the physical trajectory deviates from the path in the virtual world. While initial proofs-of-concept demonstrated the effectiveness of the techniques in preventing collisions with physical obstacles in VR labs, later research focused on identifying thresholds and factors that preserve or enhance the effectiveness of the techniques, while keeping applied manipulations to visual stimuli below just noticeable differences, i. e., making the techniques undetectable for users.

1.2. Consistent Perception of Locomotion in Virtual and Real Environments

In addition to the problem of physically confined space, there is a second challenge in constructing a fully natural locomotion interface for VEs. This challenge consists in discrepancies between perception in real and virtual environments. For example, distances in virtual worlds are underestimated in comparison to the real world [18, 19, 20, 21], visual speed during walking is underestimated in VEs [22], the distance one has traveled is underestimated [23, 24, 25], and users have other general difficulties in orienting themselves in virtual worlds [26, 27, 28]. Although this is helpful for redirected walking – because users tolerate a certain amount of inconsistency between visual and proprioceptive sensation in immersive VEs [17, 29, 30, 31, 32, 33, 34, 35, 36, 37] – it is nonetheless desirable that users have a consistent and natural experience in their virtual world.

Perceptual illusions normally break the correspondence between objective properties of visual stimuli and their subjective interpretation. Turning this principle around, visual illusions can be implemented in VE software to support a better perceptual match between the user's perception of self-motion and the user's real self-motion in the virtual environment [38]. In particular, illusions related to optic flow may change the user's perception of his self-motion in the virtual world independently of his actual self-motion in the virtual world. This may be used to tune virtual locomotion cues in order to provide natural perception of self-motion in immersive VEs.

In the scope of this article we provide a classification of different approaches in the research field of redirected walking, and give an overview of psychophysiological experiments that were conducted to answer the question of how much manipulation applied to the visual feedback in immersive VEs can be unnoticeable for the user. Moreover, we discuss how virtual self-motion perception can be changed by biasing cue integration with visual illusions, which may reduce conflicts between real and virtual self-motion perception, or may be used to improve the effectiveness of redirection techniques. We begin by describing a number of key limitations in human self-motion perception.

2. Limitations and Illusions in Visual Self-Motion Perception

When visual, vestibular, and proprioceptive sensory signals that normally support self-motion perception are in conflict, such as when visual motion stimuli are presented to stationary human subjects, vision can dominate vestibular and proprioceptive information. For example, in the illusion of linear vection [39] observers feel themselves moving although they are physically stationary simply because they are presented with large field visual motion that resembles the motion pattern normally experienced during real self-motion. This motion pattern is called optic flow, and much research has shown that humans can in principle extract self-motion information from optic flow (cf. [40, 41]). Four aspects of optic flow analysis are particularly important in the scope of this article: (1) the perception of the momentary path (direction and curvature), (2) the perception of the distance that has been traversed during a movement, (3) the perception of speed of a simulated self-motion, and (4) the perception of motion without movement.

2.1. Heading and Path Perception

The momentary direction of self-motion of a locomoting person is called *heading*. Heading perception has been extensively researched in psychophysical studies in which human subjects were presented with an optic flow through a virtual scene, and had to discriminate, for example, whether the self-motion depicted by the optic flow would pass left or right of a target location in the scene. This research found that humans are quite good at estimating momentary heading from optic flow [40, 41] but prone to perceptual errors in certain situations in which the flow field becomes ambiguous [41, 42, 43, 44].

One such situation occurs when the self motion consists of the combination of forward movement and gaze rotation, i. e. when one looks at an object during movement. When the optic flow displays a rotation of gaze around a vertical axis in addition to the forward movement of the observer the flow field looks very similar to a flow field that arises from movement along a curved path [45], and human subjects often confound the two and perceive self-motion along a curve [42, 44, 46]. This ambiguity provides a basis for visually tricking subjects into believing they move in a curve when in fact they move along a straight line, and vice versa. When human subjects are presented with flow fields that simulate true movement along a curved path they are capable to correctly perceive the momentary heading, i. e., the tangential to the path [46, 47, 48, 49, 50]. Thus, the misperception of curved motion in the situation described above suggests a perceptual bias towards interpreting rotations in the optic flow display as movement on a curved path [44]. This misperception is not due to a lack of vestibular input, since it occurs also for real movement in darkness [51]. It can be disambiguated by visual landmarks that signal body orientation with respect to the environment [52, 53, 54].

A constant static rotation of the display also induces curved walking trajectories towards a goal because it introduces an initial mismatch between the direction of the goal and the body movement [55, 56, 57, 58]. Subjects in this case quickly become aware of the mismatch and counteract it by steering a curve [59, 60].

2.2. Travel Distance

To convincingly provide the simulation of a large traversable environment in a small confined space one needs to manipulate the user's perception of the distance traversed during a movement. Visual motion during self-motion provides cues about the travel distance, such as the speeds of the visual flow. Within the VE, these cues are consistent such that they provide veridical information about the distance covered in terms of the scale of the simulation. Human subjects can use these cues to discriminate travel distance intervals [61, 62]. However, when travel distances have to be compared to static distances, even within the VE, characteristic estimation errors occur such that distances can be severely under- [23, 63] or overestimated [64], depending on the perceptual task given to the subject [65]. These experiments have suggested that humans keep track of the distance they traveled, or the remaining distance to a goal, through a process of leaky path integration [65, 66, 67].

Several further sensory and motor signals in addition to vision support travel distance perception during walking. Among them are vestibular and proprioceptive cues, stride length, step frequency, and motor efference copy signals. Success in manipulating a user's perceived travel distance in redirected walking requires to manipulate the relationship between these cues such that the user perceives a virtual (visual) distance that is different from the real (proprioceptive or motor) distance. The contribution of the various signals are seen when they are put experimentally in conflict, such as when the visual movement is larger or smaller than the physical (motor/proprioceptive) movement. This is effectively a gain change of the visual motion with respect to the motor signals and has been shown to alter the perception of travel distance [30, 68, 69].

2.3. Speed

A change in the gain between the physical movement and the visual signal also affects the perception of the speed of one's own movement. The influence of walking on visual speed perception is seen in the observation that visual speeds appear slower during walking than during standing [22] and that visual speed estimation during walking depends on various motor parameters [70, 71]. However, humans show quick adaptation to changes in gain between motor and visual parameters [68, 72]. Like the visual estimation of travel distance [62] this recalibration is based on perceived self-motion speed, not simply on visual speed [73].

Visual speed, i. e., the speed of motion signals in the optic flow during self movement, is not uniquely related to self-motion speed, since for any forward self-motion the visual velocity of any point in the scene depends on the distance of this point from the eye. Points further away move slower than points closer to the eye. Nevertheless, manipulations of visual speed affect perceived self-motion speed. In this regard visual illusions are useful that rely on the properties of human visual motion detectors to present an illusory motion percept for stimuli that are, in truth, fully stationary.

2.4. Motion Perception without Movement

The human brain senses motion via motion detectors that can be described as space-time oriented filters tuned for specific directions of motion [74]. These detectors respond to luminance signals that move from one position to another within a certain time interval, and consist of excitatory and inhibitory image regions that are aligned with a particular motion direction. The final detector response (*motion energy*) is generated by calculating the difference between the (squared) filter responses in the preferred and the opposite direction.

Because of the interaction between the two opposing directions and the excitatory and inhibitor image regions of the individual filters, a contrast inversion of a moving image can generate an illusory motion response in the reversed direction. This is known as *reversed phi* motion. This contrast inversion effect is used in the *four-stroke motion illusion* [75] to construct consistent unidirectional motion from just two frames of a motion sequence, although the position of image elements only jumps back-and-forth between frames.

Instead of the contrast inversion, which supports the reversed phi part of the four stroke motion illusion, a gray screen can be briefly presented after the two frames of a motion, resulting in the illusion of *two-stroke motion* [76]. The gray screen disrupts the detection of the opposite motion by the motion detectors and masks the jump back to the first frame of the motion resulting in continuous motion perception.

The *motion without movement* illusion [77, 78] creates a continuous motion signal from just a single static image by applying a pair of oriented edge filters to the image and re-combining them using a time-dependent blending to form a transformed view of the image. The oriented edge filters reinforce amplitude differences at luminance edges in images, which leads to a motion energy response of the motion detectors, and cause the edges to be slightly shifted forward or backward dependent on the orientation of the filter.

3. Redirection with Gain Manipulation

The previously described limitations of self-motion perception can be exploited in immersive virtual environments to redirect the user by decoupling the real and virtual traveling path. This is achieved by manipulating the visual feedback users receive about their self-motion in the virtual scene. The users compensate for the induced discrepancy between vision and other sensory signals by adapting their real (physical) traveling path. As a result, users may walk further or shorter, rotate further or shorter, or walk on curve-like trajectories while apparently walking straight in the VE. To achieve the redirection of users, gains are applied to the tracked real-world movements consisting of translations, rotations, or a combination of both. By combining both types of movements users can navigate on curve-like trajectories. As the gains are applied on the motion of the camera, all objects in the scene are manipulated in the same manner. In the following, we describe the technical implementation of the gain manipulation for translations, rotations, and path curvatures.

3.1. Translation

Assuming that the coordinate systems of the tracked lab space and virtual world are calibrated and registered, a tracked change of the user's position defined by the vector $T_{\text{real}} = P_{\text{cur}} - P_{\text{pre}}$, with P_{cur} the current position and P_{pre}

the previous position, T_{real} is mapped one-to-one to the virtual camera. Then, the virtual camera is moved by $|T_{\text{real}}|$ units in the corresponding direction in the virtual world coordinate system. The tracking system updates the change of position several times per second as long as the user remains within the range of the tracking system. A translation gain $g_T \in \mathbb{R}$ is defined by the quotient of the mapped virtual world translation T_{virtual} and the tracked real world translation T_{real}, i. e., $g_T := \frac{T_{\text{virtual}}}{T_{\text{real}}}$. When a translation gain g_T is applied to a translational movement T_{real} the virtual camera is moved by the vector $g_T \cdot T_{\text{real}}$ in the corresponding direction. This means that if $g_T = 1$ the virtual scene remains stable considering the head's position change. In the case $g_T > 1$ the displacement in the virtual scene is greater than in the lab space, whereas a gain $g_T < 1$ causes a smaller displacement in the virtual scene compared to the displacement in the lab space. In practical implementations, the translation gains are usually only applied in the main walk direction, and not to lateral or vertical head movements [18].

3.2. Rotation

Real-world head rotations can be specified by a vector consisting of three angles, i. e., $R_{\text{real}} := (\textit{pitch}_{\text{real}}, \textit{yaw}_{\text{real}}, \textit{roll}_{\text{real}})$. The tracked orientation change is applied to the virtual camera. Rotation gains are defined for each component (pitch, yaw, roll) of the rotation. A rotation gain $g_R \in \mathbb{R}$ is defined by the quotient of the considered component of a virtual world rotation R_{virtual} and the real world rotation R_{real}, i. e., $g_R := \frac{R_{\text{virtual}}}{R_{\text{real}}}$. When a rotation gain g_R is applied to a real world rotation α, the virtual camera is rotated by $\alpha \cdot g_R$ instead of α. This means that if $g_R = 1$ the virtual scene remains stable considering the head's orientation change. In the case $g_R > 1$ the rotation of the virtual scene is greater than the head turn, whereas a gain $g_R < 1$ causes a smaller rotation of the virtual scene compared to the head turn in the lab space. For instance, if the user rotates his head by 90°, a gain $g_R = 1$ maps this motion one-to-one to a 90° rotation of the virtual camera in the VE. The appliance of a gain $g_R = 0.5$ means that the user has to rotate the head by 180° physically in order to achieve a 90° virtual rotation; a gain $g_R = 2$ means that the user has to rotate the head by only 45° physically in order to achieve a 90° virtual rotation. Rotation gains are usually applied to yaw rotations, which are the most often manipulated movements for redirected walking [17, 31, 32, 33, 34, 35].

3.3. Path Curvature

Instead of multiplying gains with translations or rotations, offsets can be added to real-world movements. In particular, if a translational movement of a user is tracked in the lab space, a rotational offset can be added to the virtual camera orientation, e. g., rotating the camera around the center of the user while the user walks straight. For example, when the user moves straight ahead, iterative camera rotations to one side enforce the user to walk along a curve in the opposite direction in order to stay on a straight path in the virtual world. If the injected manipulations are reasonably small, the user will unknowingly compensate for these offsets. Curvature gains $g_C \in \mathbb{R}$ are used to describe the resulting bend of a real-world path. The curve is determined by a circular arc with radius r, and we define $g_C := \frac{1}{r}$. In case no curvature is applied it is $r = \infty \Rightarrow g_C = 0$, whereas if the curvature causes the user to rotate by 90° clockwise after $\frac{\pi}{2}$m the user has covered a quarter circle with radius $r = 1 \Rightarrow g_C = 1$.

4. Perceptual Thresholds for Gain Manipulations

Gain manipulations are effective ways to decouple the user's path in the virtual world from the path in the real world (Figure 2), and to enable path modification in the real world that confine the real movement to a smaller space than the virtual movement. However, in order to avoid breaks of the immersion in the virtual world [79] it is desirable that the manipulations go unnoticed by the user. Hence, one wants to decouple the user's real movement from his virtual movement *without the user noticing*. This is possible because of the limitations of self-motion perception described above, but obviously only within bounds. Thus, one must ask what the thresholds for perception of deviations between the real and the virtual movement are. As long as the manipulations of the scene stay below these thresholds, the displacement of the virtual world might be faster, slower or even curve-like instead of straight while the user believes to walk straight at his usual pace.

Thresholds for gain manipulations were determined in a series of experiments by Steinicke et al. [80]. These experiments used a *two-alternative forced-choice* (2AFC) task in which the subject was asked whether he perceived a physical movement as *smaller* or *greater* than the virtual movement that was displayed in the HMD that he wore. In each trial, the subject had to perform a predetermined movement (either a rotation or a translation), and the HMD displayed a movement that was either smaller than the real one ($g < 1$) or it was greater ($g > 1$). The performance was measured as the proportion of "greater" responses as a function of g. The value of g for which the subject responded equally often with "greater" and "smaller" gives the *point of subjective equality* (PSE). It represents the gain at which the subject judges the physical and the virtual movement as identical. If the PSE is not identical to $g = 1$ the subject over- or underestimates the virtual movement with respect to the real movement. If g becomes increasingly larger or smaller than the PSE, differences between the virtual and the real movement become more noticeable. The detection threshold is defined as the gain at which the proportion of correct responses was 0.75. Because the gain can be larger or smaller than the PSE, there is a separate threshold for gains larger than 1 (the upper detection threshold (UDT)) and for gains smaller than 1 (the lower detection threshold (LDT)).

Figure 3a and b illustrate the PSEs together with the detection thresholds for rotations and translations. Rotation angles can be increased up to a gain of $g_R = 1.24$ or decreased down to a gain of $g_R = 0.67$ without the user noticing. Evaluating rotation gains using a 3rdTech HiBall low-latency tracking system, Bruder et al. [81] determined thresholds of $g_R = 1.26$ and $g_R = 0.68$. In similar experiments using a Barco CRT projector to emulate a zero-latency HMD, Jerald et al. [82] found ranges of head rotations to go unnoticed by subjects between $g_R = 1.052$ and $g_R = 0.887$, which are tighter than found for current-state HMDs and tracking systems. Both results indicate that users appear to be more sensitive to scene motion if the scene moves against the direction of head motion than if the scene moves with the head motion. The results are consistent with the asymmetric sensitivity to virtual head rotations observed by Jaekl et al. [36], who found in an experiment aimed at determining perceptually "stable" head yaw rotations a shift towards a gain of $g_R = 1.15$. Jerald and Steinicke [83] discuss potential reasons for this phenomenon. Analyzing body rotations over different angles in immersive VEs, Bruder et al. [84] found similar thresholds, as well as the tendency that gains applied to smaller rotation angles appear less detectable by users, which provides interesting guidelines for practitioners. In experiments evaluating the effects of attention on detectability of rotation gains, Peck et al. [31, 85] found that the practically applicable ranges of rotation manipulations can be significantly increased if "distractors" are embedded in the visual stimulus.

For translations, Steinicke et al. [80] found that virtual translations can be scaled up to a gain of $g_T = 1.26$ or scaled down to a gain of $g_T = 0.86$ (Figure 3b). Bruder et al. [81] found thresholds of $g_T = 1.29$ and $g_T = 0.87$ for an experimental setup using a different HMD, tracking system, visual stimulus and subject groups. While in these experiments subjects were instructed to focus on scene motions, anecdotal evidence suggests that translation gains up-scaling virtual motions by up to $+100\%$ are still not considered as overly distracting by users if they are engaged in a task in the virtual environment [35].

Steinicke et al. [80] also investigated detection thresholds for path curvature during manipulations of curvature gain. Subjects walked a straight path in the VE, which was physically bent by a curvature gain g_C either to the left or to the right. Subjects then had to judge if the physical path was bent to the left or to the right. Analysis of the response data showed that the user's path can be bent without the user noticing by $13°$ ($g_C = 0.045$) to the left or to the right after walking a 5m distance (Figure 3c). Thus, a straight path in the VE can be turned into a circular arc in the real world with a radius of approximately 22m. Therefore, if the lab space covers an area of approximately $40\text{m}\times 40\text{m}$, the user can perform unlimited straight movements in the VE, while in fact he is walking on a circular arc in the physical world. These results approximate space requirements suggested by Razzaque et al. [17], who pointed out that a VR lab space of approximately $60\text{m}\times 60\text{m}$ would be sufficient to render vestibular feedback to changes in heading entirely undetectable to users. In a different experiment, Bruder et al. [81] found a radius of 14.92m sufficient for 75% detection thresholds, which may be explained by the different physical setup, visual stimulus and subject groups, which have been suggested as potential factors affecting detectability of manipulations [17]. Investigating reasons for varying sensitivity to curvature gains, Neth et al. [86] observed that the detectabiliy of curvatures was reduced for slower translation velocities, whereas higher velocities resulted in increased sensitivity to curvatures and tighter ranges of possible manipulations. Along the lines of adaptive curvature controllers proposed by Engel et al. [87], which were based on determining detection thresholds for each user before exposure to virtual tasks, they suggest to incorporate a control logic into practical redirected walking implementations that derives maximum curvature gains from user behavior. This approach has the potential to result in less space requirements than imposed by constant manipulations based on the average or lowest individual detection thresholds measured over a population of test subjects.

These results show that redirected walking is a useful, low-cost technique to implement real walking in VEs, even for large VEs and small physical spaces. One has to note, moreover, that the gain thresholds obtained in these experiments are minimum values, since the subjects were explicitly attending to the differences between real and virtual movements. If they do not attend to these differences thresholds are likely to be even higher. In addition, distractors can be added to the scene that shift away the user's attention during gain manipulations [85]. Moreover, rotation, translation and curvature gains may be used in combination. Rotation gains, in particular, can be applied during saccadic eye movements when the user is stationary, because saccadic suppression will mask the visual rotation further. Thus, when the virtual scene invites many turns, a combination of rotation and translation gains can make the virtual space almost infinitely large [87].

5. Tuning Ego-Speed Perception with Self-Motion Illusion Techniques

When the mapping of a user's movements from the real world to a virtual scene is changed with gain manipulations, a quantitative discrepancy between real and virtual motions is introduced. This discrepancy is in addition to discrepancies that exist between perception in real and virtual environments in general. Visual illusions can be used to remedy these discrepancies. It is possible to affect the user's perception of ego-speed, for example, via apparent self-motion illusions by manipulating optic flow fields [38]. These illusions can tune a user's ego-speed judgments to compensate for over- or underestimations of speed or travel distance that are often found in immersive VEs. Moreover, they can also be used to shift or widen the applicable ranges for gain manipulations discussed in Section 4. Below we will discuss how these illusions can be implemented in VEs and how they affect the user's self-motion perception.

5.1. Adding Visual Ego-Speed Signals to Virtual Environments

The principle behind the different techniques is the following: The view that the user sees in the HMD is modified by adding motion signals to the image that stimulate motion detectors and cause the perceived self motion to be either smaller or larger than the true self-motion. The additional motion signals are blended into the image and need to be consistent with the direction of the user's real self-motion in order to affect only speed components. The visual speed of the optic flow illusions is thus specified relative to the user's virtual self-motion, which is known from the head tracking and the elapsed time between two frames.

As described in Section 3, the actual motion of the user can be scaled with translation gains g_T, causing the user's virtual motion to deviate from the real-world movement with $g_T \cdot T_{\text{real}}$. In the same way, additional motion signals from illusory motions can be scaled with gains $g_{T_I} \in \mathbb{R}$ relative to the scene motion with $(g_{T_I} + g_T) \cdot T_{\text{real}}$. For instance, $g_{T_I} > 0$ results in an increased motion speed, whereas $g_{T_I} < 0$ results in a decreased motion speed of the visual illusion on top of the virtual scene motion generated with gain g_T from the user's movement.

Figure 5 illustrates a number of different techniques for adding visual ego-speed signals to virtual environments [38]. In Figures 5a-c *layered optic flow fields* are transparently blended over the virtual scene: particle flow fields (a), sinusoidal gratings (b) or a surface textured with a seamless tiled pattern approximating those in the virtual view (c). The optic flow stimuli can be steered 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 translations as described above. The speed can be modulated with gains $g_{T_I} \in \mathbb{R}$ applied to the translational components of one-to-one scene motion for computation of the displacement vectors.

Figures 5d-f show illusions based on the properties of human motion detectors described in Section 2.4. Figure 5d shows an application of *four-stroke motion* applied to the peripheral parts of the scene. In this illusion, two images A and B as well as the contrast reversed images A^c and B^c are displayed in the following looped sequence to the viewer: $A \rightarrow B \rightarrow A^c \rightarrow B^c$. This results in a perceived constant motion $A \rightarrow B$, although the position of image elements only jumps back-and-forth between frames. In Figure 5e, a single motion signal $A \rightarrow B$ together with masking by a gray inter-frame stimulus to support continuous motion perception is used in a variant of *two-stroke motion*. Figure 5f shows an application of the *motion without movement* illusion. This illusion is constructed from just a single still frame by applying a pair of oriented edge filters, i. e., second derivative of a Gaussian and its Hilbert transform [78]. The so-generated two images are blended over time to create a continuous motion signal from a single static image (see [38] for implementation details). In all three cases, manipulations of the images are applied that induce additional motion stimulation on top of any movement of the scene view that is due to the movement of the user.

5.2. Blending Techniques

The additional motion signals in Figure 5 can be applied to the entire virtual view, or, as was done in the figure, only in specific regions of the user's view. Limiting the areas in which the manipulations are applied is useful to avoid too much interference with the perception of the VE and the immersion. Visual illusions in immersive VEs may distract the user, in particular, if they occur in the region of the virtual scene on which the user is focusing. Thus, it makes sense to apply the manipulation only to the peripheral regions of the view i. e., regions outside the center of interests but still within the view provided by the visual display device. This preserves accurate vision with highest acuity around the optical line-of-sight (Figure 4). Moreover, such a peripheral restriction is also well matched to the properties of the human visual system, which, in the periphery, is highly sensitive to motion and has only poor spatial resolution. Perception of self-motion therefore relies to a large part on peripheral motion stimulation.

Pixels in the central region can be rendered with the camera state defined by one-to-one or scaled mappings, and an illusory motion algorithm can be used only for the peripheral region. To provide a seamless transition between the central and peripheral regions of the views, i. e., to provide illusory motion signals only in the periphery, basic circular alpha blending proved to be applicable [38] (Figure 5). Thus, potential visual distortions in the periphery do not disturb foveal information of objects the user is focusing on.

While, as mentioned above, the human visual system collects self-motion information from the peripheral parts of the visual field, a further specialization exists for the ground plane. In natural optic flow fields, the ground plane, respectively the lower part of the visual field, contains the most reliable information about self-movement [41, 88, 89, 90, 91]. These cues provide information about the walking direction, as well as velocity of the observer. In contrast to peripheral stimulation, visual modulations can thus be applied to the ground plane exclusively (see Figure 4). Therefore, an adaptive alpha blending can be incorporated. Pixels corresponding to objects in the scene can be rendered with the camera state defined by one-to-one or scaled mappings, and an illusory motion algorithm can be used only for the pixels that are flagged to correspond to the ground surface. As a result, users maintain a clear view to focus objects in the visual scene, while optic flow cues that originate from the ground can be manipulated.

6. Effectiveness of Ego-Speed Tuning

Bruder et al. [38] measured the effect of optic flow illusions on ego-speed judgments and compared the efficacy of the different illusion and blending techniques. As in Steinicke et al. [80], subjects were asked in a 2AFC procedure whether the physical movement was *smaller* or *greater* than the virtual movement in the HMD. Different illusory motions were blended over the visual self-motion displayed in the HMD with gains g_{T_I} varying between -1 and 1, thus attenuating or amplifying visual ego-speed signals. For each condition, it was determined how much the PSE shifted with the addition of the illusory motion. These measurements were taken for four different settings of the translational gain g_T between the virtual and the real movement: the one-to-one mapping ($g_T = 1$), the PSE obtained in the study of Steinicke et al. [80] ($g_T = 1.07$), and the lower ($g_T = 0.86$) and upper $g_T = 1.26$) detection thresholds obtained in that study (cf. Section 4).

They found that the four-stroke, two-stroke, and motion without movement illusions significantly affected the judgments of virtual locomotor speed, and shifted the PSE at which virtual and real movement seemed identical to the subject. For layered motion stimuli only the infinite surface texture affected speed judgments; particle flow fields and sinusoidal gratings rather gave the impression of a transparent overlay of independent motion. Ground plane blending was typically as effective as blending in the full periphery.

The effectiveness of illusory motion stimuli on ego-speed perception can be used for two improvements in VE perception. On the one hand, the typical underestimation of virtual walking in case of a one-to-one mapping from real to virtual movements (such as the 7% underestimation observed by Steinicke et al. [80]) can be compensated by applying a slightly increased illusory optic flow, thus making one's virtual ego-speed appear identical to one's physical motion in immersive VEs. On the other hand, added illusory motion can counter the changes of virtual ego-speed that occur when gain manipulations are used to redirect users in immersive VEs (see Section 3) . For example, at a translation gain of $g_T = 0.86$, i.e., the lower detection threshold, adding four-stroke motion with a gain $g_{T_I} = 1.2$ leads to perceived equality between virtual and physical motion. Thus, an increased or decreased illusory optic flow can be used to shift the perceived ego-motion towards the PSE even when translation gains larger or smaller than 1 are applied to virtual self-motion. Therefore, applying even larger gains than the detection thresholds identified by Steinicke et al. [80] becomes possible, as illusory optic flow stimuli can increase the range of undetectable motion manipulations in redirected walking applications.

7. Conclusion and Future Directions

In this article we have reviewed and discussed many perceptual aspects related to natural locomotion in current immersive VEs. We have shown how psychophysiological findings about self-motion perception can be exploited by practitioners in the field of VR to enable omni-directional and unlimited walking in virtual worlds with redirected walking techniques. We have discussed experiments and studies in which the effectiveness of different approaches is evaluated and compared. Finally, we have described recent work on how the perception of self-motion in VEs can be changed with illusions related to optic flow, independent of a user's true virtual self-motion. The described techniques open up new vistas for providing consistent self-motion cues in immersive VEs.

While the discussed approaches have shown their potential to enable natural locomotion in immersive VEs, evaluations of these techniques have revealed certain limitations. For instance, a clockwise rotation of the virtual view in a HMD can cause the user to unknowingly compensate by walking a circular arc in the counter-clockwise direction. However, the psychophysical experiments have revealed that when users focus on their walking direction, the illusion of walking on a straight trajectory in the VE is only preserved if the physical trajectory follows a circular path of usually more than 40 meters in diameter, which proves to be a strong practical limitation in typical lab settings. While theoretically several users may be redirected in the same physical lab space [92], one has to avoid collisions between users, which increases the required space even further.

However, the thresholds obtained in the experiments represent quite conservative estimates. The attention of the subjects was directed towards the deviations and the final thresholds resulted from the mean across all subjects. When the detection of deviations from natural walking is not in the focus of attention, such as when the user in an interaction focuses on some task within the environment higher gains might go unnoticed by the user. Secondly, simply taking the mean threshold over all subjects bears the problem that some individuals may detect deviations already at lower thresholds whereas others detect deviations only at higher thresholds. Individual gain estimations might increase the range of possible gain manipulations for some users. To ensure that gain manipulations go unnoticed by all users without the extra time to measure each individually one could alternatively take the lowest individual threshold found in a representative sample. However, the obtained thresholds would now be comparatively low and, of course, even lower than the overall mean. Therefore, if the gain estimation procedure could be reduced to a simple calibration for an individual user, individual gain estimation constitutes the best solution to achieve the optimal range of manipulations for every user.

Considering that no technique presented so far is generally applicable in VR labs of much smaller dimensions, practitioners in the field of virtual locomotion face the problem of either designing hybrid approaches based on a combination of different techniques that may suffice to make redirected walking applicable in typical VR labs, or improving the effectiveness of the existing approaches [13]. We have shown that self-motion illusions related to optic flow can be applied to change the perception of ego-speed in a VE, which has great potential to improve the effectiveness of redirection approaches. A key challenge in the field of virtual locomotion remains a more general understanding of the limitations of movement perception in immersive VEs, and to identify how further perceptual illusions may be exploited to make redirected walking generally applicable.

Another challenge concerns the prediction of a user's virtual behavior. Implementations of redirected walking require reliable prediction of a user's path in the VE to derive physical paths on which the user is guided in the lab space. With reliable path prediction in the VE unlimited and omni-directional walking becomes possible, during which users cannot observe discrepancies between physical and virtual paths. Moreover, users may be guided on physical paths to desired proxy props which provide passive haptic feedback during tangible interaction [35]. Such path prediction, however, raises two key challenges. The first is to define a physical path along which the user can be guided safely and without noticing any deviations between physical and virtual path. This path planning should be based on perceptual thresholds but it also needs to take into account future actions of the user. The second challenge is related to these actions. For efficient redirection it would be required to know in advance what the user will do in order to find the most appropriate situations in which the manipulations can be applied. Short-term prediction could be implemented via extrapolation of movement trajectories, whereas long-term prediction becomes only possible if the user's goals of the locomotion can be deduced. Therefore, a semantic model of the VE is required and potential goals have to be known.

Another open issue is the effect of adaptation to motion manipulations in VEs. Humans tend to adapt to gain changes between physical and visual movement if these changes are applied consistently over a certain time (e. g., [30, 68, 69, 72]). Such adaptive properties of the perceptual system also open up possibilities for manipulation, which have not been investigated yet in this context. Adaptation requires that the user stays and acts within a VE for a longer time. This transforms the user's perception of the VE such that he learns to interact with the VE in a particular way. The potential of these learning effects remains to be explored, but will provide interesting directions in the area of redirected walking.

[1] M. Whitton, J. Cohn, P. Feasel, S. Zimmons, S. Razzaque, B. Poulton, B. M. und F. Brooks, Comparing VE locomotion interfaces, in: Proceedings of Virtual Reality, IEEE, 2005, pp. 123–130.

[2] L. Bouguila, M. Sato, Virtual locomotion system for large-scale virtual environment, in: Proceedings of Virtual Reality, IEEE, 2002, pp. 291–292.

[3] L. Bouguila, M. Sato, S. Hasegawa, H. Naoki, N. Matsumoto, A. Toyama, J. Ezzine, D. Maghrebi, A new step-in-place locomotion interface for virtual environment with large display system, in: Proceedings of SIGGRAPH, ACM, 2002, p. 63.

[4] J. L. Souman, P. R. Giordano, M. Schwaiger, I. Frissen, T. Thümmel, H. Ulbrich, A. De Luca, H. H. Bülthoff, M. O. Ernst, CyberWalk: Enabling unconstrained omnidirectional walking through virtual environments, ACM Trans. Appl. Percept. 8 (4) (2011) 1–22.

[5] H. Iwata, Y. Hiroaki, H. Tomioka, Powered Shoes, SIGGRAPH 2006 Emerging Technologies (28).

[6] H. Iwata, H. Yano, H. Fukushima, H. Noma, CirculaFloor, IEEE Comput. Graph. Appl. 25 (1) (2005) 64–67.

[7] M. Schwaiger, T. Thümmel, H. Ulbrich, Cyberwalk: Implementation of a ball bearing platform for humans, in: Proceedings of HCI, 2007, pp. 926–935.

[8] J. Feasel, M. Whitton, J. Wendt, LLCM-WIP: Low-latency, continuous-motion walking-in-place, in: Proceedings of Symposium on 3D User Interfaces, IEEE, 2008, pp. 97–104.

[9] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, F. P. J. Brooks, Walking $>$ walking-in-place $>$ flying, in virtual environments, in: Proceedings of the Conference on Computer Graphics and Interactive Techniques, 1999, pp. 359–364.

[10] R. A. Ruddle, S. Lessels, The benefits of using a walking interface to navigate virtual environments, ACM Trans. Comput. Hum. Interact. 16 (1 (5)) (2009) 1–5.

[11] J. Su, Motion compression for telepresence locomotion, Presence: Teleoperators and Virtual Environments 4 (16) (2007) 385–398.

[12] B. Williams, G. Narasimham, T. P. McNamara, T. H. Carr, J. J. Rieser, B. Bodenheimer, Updating orientation in large virtual environments using scaled translational gain, in: Symposium on Applied Perception in Graphics and Visualization, Vol. 153, ACM, 2006, pp. 21–28.

[13] E. Suma, G. Bruder, F. Steinicke, D. M. Krum, M. Bolas, A taxonomy for

deploying redirection techniques in immersive virtual environments, in: Proceedings of Virtual Reality, IEEE, 2012, pp. 43–46.

[14] E. Suma, D. M. Krum, S. Finkelstein, M. Bolas, Effects of redirection on spatial orientation in real and virtual environments, in: Proceedings of Symposium on 3D User Interfaces, IEEE, 2011, pp. 35–38.

[15] E. A. Suma, S. Clark, S. Finkelstein, Z. Wartell, M. Krum, M. Bolas, Leveraging change blindness for redirection in virtual environments, in: Proceedings of Virtual Reality, IEEE, 2011, pp. 159–166.

[16] F. Steinicke, G. Bruder, K. H. Hinrichs, P. Willemsen, Change blindness phenomena for stereoscopic projection systems, in: Proceedings of Virtual Reality, IEEE, 2010, pp. 187–194.

[17] S. Razzaque, Redirected walking, Ph.D. thesis, University of North Carolina at Chapel Hill (2005).

[18] V. Interrante, L. Anderson, B. Ries, Distance perception in immersive virtual environments, revisited, in: Proceedings of Virtual Reality, IEEE, 2006, pp. 3–10.

[19] J. M. Plumert, J. K. Kearney, J. F. Cremer, K. Recker, Distance perception in real and virtual environments, in: 2 (Ed.), ACM Trans. Appl. Percept., Vol. 3, 2004, pp. 216–233.

[20] J. M. Loomis, J. M. Knapp, Visual perception of egocentric distance in real and virtual environments, in: Virtual and adaptive environments, Mahwah, 2003, pp. 21–46.

[21] W. B. Thompson, P. Willemsen, A. A. Gooch, S. H. Creem-Regehr, J. M. Loomis, A. C. Beall, Does the quality of the computer graphics matter when judging distances in visually immersive environments?, Presence 13 (5) (2004) 560–571.

[22] T. Banton, J. Stefanucci, F. Durgin, A. Fass, D. Proffitt, The perception of walking speed in a virtual environment, Presence 14 (4) (2005) 394–406.

[23] H. Frenz, M. Lappe, M. Kolesnik, T. Bührmann, Estimation of travel distance from visual motion in virtual environments, ACM Trans. Appl. Percept. 3 (4) (2007) 419–428.

[24] B. G. Witmer, P. B. Kline, Judging perceived and traversed distance in virtual environments, Presence: Teleoperators and Virtual Environments 7 (2) (1998) 144–167.

[25] J. M. Knapp, J. M. Loomis, Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments, Presence: Teleoperators and Virtual Environments 13 (5) (2004) 572–577.

[26] B. Riecke, J. Wiener, Can people not tell left from right in VR? point-to-origin studies revealed qualitative errors in visual path integration, in: Proceedings of Virtual Reality, IEEE, 2007, pp. 3–10.

[27] M. J. Kearns, W. H. Warren, A. P. Duchon, M. J. Tarr, Path integration from optic flow and body senses in a homing task, Perception 31 (3) (2002) 349–374.

[28] P. Peruch, M. May, F. Wartenberg, Homing in virtual environments: Effects of field of view and path layout, Perception 26 (3) (1997) 301–311.

[29] E. Hodgson, E. Bachmann, D. Waller, Redirected walking to explore virtual environments: Assessing the potential for spatial interference, ACM Trans. Appl. Percept. 8 (4) (2011) 1–22.

[30] H.-J. Sun, J. L. Campos, G. S. W. Chan, Multisensory integration in the estimation of relative path length, Exp. Brain Res. 154 (2004) 246–254.

[31] T. Peck, M. Whitton, H. Fuchs, Evaluation of reorientation techniques for walking in large virtual environments, in: Proceedings of Virtual Reality, IEEE, 2008, pp. 121–128.

[32] E. Burns, S. Razzaque, A. T. Panter, M. Whitton, M. McCallus, F. Brooks, The hand is slower than the eye: A quantitative exploration of visual dominance over proprioception, in: Proceedings of Virtual Reality, IEEE, 2005, pp. 3–10.

[33] J. Jerald, T. Peck, F. Steinicke, M. Whitton, Sensitivity to scene motion for phases of head yaws, in: ACM Symposium on Applied Perception in Graphics and Visualization, 2008, pp. 155–162.

[34] L. Kohli, E. Burns, D. Miller, H. Fuchs, Combining passive haptics with redirected walking, in: Proceedings of Conference on Augmented Tele-Existence, Vol. 157, ACM, 2005, pp. 253–254.

[35] F. Steinicke, G. Bruder, T. Ropinski, K. H. Hinrichs, Moving towards generally applicable redirected walking, in: Proceedings of the Virtual Reality International Conference, IEEE Press, 2008, pp. 15–24.

[36] P. M. Jaekl, R. S. Allison, L. R. Harris, U. T. Jasiobedzka, H. L. Jenkin, M. R. Jenkin, J. E. Zacher, D. C. Zikovitz, Perceptual stability during head

movement in virtual reality, in: Proceeding of Virtual Reality, IEEE, 2002, pp. 149–155.

[37] J. L. Campos, P. Byrne, H.-J. Sun, The brain weights body-based cues higher than vision when estimating walked distances, Eur. J. Neurosci. 31 (10) (2010) 1889–1898.

[38] G. Bruder, F. Steinicke, P. Wieland, M. Lappe, Tuning self-motion perception in virtual reality with visual illusions, IEEE Trans. Vis. Comput. Graphics 18 (7) (2012) 1068–1078.

[39] A. Berthoz, B. Pavard, L. R. Young, Perception of linear horizontal self-motion induced by peripheral vision (linearvection): basic characteristics and visual-vestibular interactions, Exp. Brain Res. 23 (1975) 471–489.

[40] W. H. J. Warren, Visually controlled locomotion: 40 years later, Ecolog. Psychol. 10 (1998) 177–219.

[41] M. Lappe, F. Bremmer, A. V. van den Berg, Perception of self-motion from visual flow, Trends. Cogn. Sci. 3 (9) (1999) 329–336.

[42] C. S. Royden, Analysis of misperceived observer motion during simulated eye rotations, Vis. Res. 34 (23) (1994) 3215–3222.

[43] A. Grigo, M. Lappe, Dynamical use of different sources of information in heading detection from retinal flow, J. Opt. Soc. Am. A 16 (9) (1999) 2079–2091.

[44] R. J. Bertin, I. Israël, M. Lappe, Perception of two-dimensional, simulated ego-motion trajectories from optic flow, Vis. Res. 40 (21) (2000) 2951–2971.

[45] M. Lappe, J. P. Rauschecker, Heading detection from optic flow, Nature 369 (6483) (1994) 712–713.

[46] L. Li, J. C. K. Cheng, Perceiving path from optic flow, J. Vis. 11 (1) (2011) 1–15.

[47] W. H. Warren, D. R. Mestre, A. W. Blackwell, M. W. Morris, Perception of circular heading from optical flow, J. Exp. Psychol. Hum. Percept. Perform. 17 (1991) 28–43.

[48] L. S. Stone, J. A. Perrone, Human heading estimation during visually simulated curvilinear motion, Vis. Res. 37 (5) (1997) 573–590.

[49] L. Li, J. Warren, W. H., Path perception during rotation: influence of instructions, depth range, and dot density, Vis. Res. 44 (2004) 1879–1889.

[50] L. Li, J. Chen, X. Peng, Influence of visual path information on human heading perception during rotation, J. Vis. 9 (3) (2009) 1–14.

[51] Y. P. Ivanenko, R. Grasso, I. Israel, A. Berthoz, The contribution of otoliths and semicircular canals to the perception of two-dimensional passive whole-body motion in humans, J. Physiol. (Lond) 502 (1) (1997) 223–233.

[52] L. Li, W. H. J. Warren, Perception of heading during rotation: sufficiency of dense motion parallax and reference objects, Vis. Res. 40 (0042-6989 (Print)) (2000) 3873–3894.

[53] R. J. V. Bertin, I. Israel, Optic-flow-based perception of two-dimensional trajectories and the effects of a single landmark, Perception 34 (4) (2005) 453–475.

[54] C. S. Royden, J. M. Cahill, D. M. Conti, Factors affecting curved versus straight path heading perception, Percept. Psychophys. 68 (2) (2006) 184–193.

[55] S. Rushton, J. M. Harris, M. R. Lloyd, J. P. Wann, Guidance of locomotion on foot uses perceived target location rather than optic flow, Curr. Biol. 8 (1998) 1191–1194.

[56] J. M. Harris, B. J. Rogers, Going against the flow, Trends. Cogn. Sci. 3 (12) (1999) 449–450.

[57] M. Lappe, F. Bremmer, A. V. van den Berg, Going against the flow - reply, Trends. Cogn. Sci. 3 (1999) 450.

[58] J. Warren, W. H., B. A. Kay, W. D. Zosh, A. P. Duchon, S. Sahuc, Optic flow is used to control human walking, Nat. Neurosci. 4 (2) (2001) 213–216.

[59] L. Li, L. S. Stone, J. Chen, Influence of optic-flow information beyond the velocity field on the active control of heading, J. Vis. 11 (4) (2011) 1–16.

[60] L. Li, J. C. K. Cheng, Heading but not path or the tau-equalization strategy is used in the visual control of steering toward a goal, J. Vis. 11 (12) (2011) 1–12.

[61] F. Bremmer, M. Lappe, The use of optical velocities for distance discrimination and reproduction during visually simulated self-motion, Exp. Brain Res. 127 (1) (1999) 33–42.

[62] H. Frenz, F. Bremmer, M. Lappe, Discrimination of travel distances from 'situated' optic flow, Vis. Res. 43 (20) (2003) 2173–2183.

[63] H. Frenz, M. Lappe, Absolute travel distances from optic flow, Vis. Res. 45 (13) (2005) 1679–1692.

[64] F. P. Redlick, M. Jenkin, L. R. Harris, Humans can use optic flow to estimate distance of travel, Vis. Res. 41 (2) (2001) 213 – 219.

[65] M. Lappe, M. Jenkin, L. R. Harris, Travel distance estimation from visual motion by leaky path integration, Exp. Brain Res. 180 (1) (2007) 35–48.

[66] M. Lappe, H. Frenz, Visual estimation of travel distance during walking, Exp. Brain Res. 199 (3-4) (2009) 369–375.

[67] M. Lappe, M. Stiels, H. Frenz, J. M. Loomis, Keeping track of the distance from home by leaky integration along veering paths, Exp. Brain Res. 212 (1) (2011) 81–89.

[68] J. J. Rieser, H. Pick, D. H. Ashmead, A. E. Garing, Calibration of human locomotion and models of perceptual-motor organization, J. Exp. Psychol. Hum. Percept. Perform. 21 (1995) 480–497.

[69] H.-J. Sun, J. L. Campos, M. Young, G. S. W. Chan, The contributions of static visual cues, nonvisual cues, and optic flow in distance estimation, Perception 33 (2004) 49–65.

[70] F. Durgin, K. Gigone, R. Scott, Perception of visual speed while moving, J. Exp. Psychol. Hum. Percept. Perform. 31 (2) (2005) 339–353.

[71] F. H. Durgin, C. Reed, C. Tigue, Step frequency and perceived self-motion, ACM Trans. Appl. Percept. 4 (1 (5)) (2007) 1–23.

[72] A. Pelah, H. B. Barlow, Visual illusion from running, Nature 381 (1996) 283.

[73] B. J. Mohler, W. B. Thompson, S. H. Creem-Regehr, H. L. J. Pick, W. H. J. Warren, Visual flow influences gait transition speed and preferred walking speed, Exp. Brain Res. 181 (2) (2007) 221–228.

[74] E. H. Adelson, J. R. Bergen, Spatiotemporal energy models for the perception of motion, J. Opt. Soc. Am. A 2 (2) (1985) 284–298.

[75] S. M. Anstis, B. J. Rogers, Illusory continuous motion from oscillating positive-negative patterns: implications for motion perception, Perception 15 (5) (1986) 627–640.

[76] G. Mather, Two-stroke: a new illusion of visual motion based on the time course of neural responses in the human visual system, Vis. Res. 46 (13) (2006) 2015–2018.

[77] W. T. Freeman, E. H. Adelson, D. J. Heeger, Motion without movement, SIGGRAPH Comput. Graphics 25 (4) (1991) 27–30.

[78] L. Antonov, R. Raskar, Implementation of motion without movement on real 3D objects, Tech. Rep. TR-04-02, Computer Science, Virginia Tech (2002).

[79] M. Slater, Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments, Trans. of the Royal Society B: Biological Sciences 364 (1535) (2009) 3549–3557.

[80] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, M. Lappe, Estimation of detec-

tion thresholds for redirected walking techniques, IEEE Trans. Vis. Comput. Graph. 16 (1) (2010) 17–27.

[81] G. Bruder, V. Interrante, L. Phillips, F. Steinicke, Redirecting walking and driving for natural navigation in immersive virtual environments, IEEE Trans. Vis. Comput. Graph. 14 (4) (2012) 538–545.

[82] J. Jerald, M. Whitton, F. Brooks, Jr., Scene-motion thresholds during head yaw for immersive virtual environments, ACM Trans. Appl. Percept. 9 (4) (2012) 1–23.

[83] J. Jerald, F. Steinicke, Scene instability during head turns, in: Proceedings of the IEEE VR Workshop on Perceptual Illusions in Virtual Environments, 2009, pp. 4–6.

[84] G. Bruder, F. Steinicke, K. H. Hinrichs, M. Lappe, Reorientation during body turns, in: Proceedings of the Joint Virtual Reality Conference, 2009, pp. 145–152.

[85] T. C. Peck, H. Fuchs, M. C. Whitton, Evaluation of reorientation techniques and distractors for walking in large virtual environments, IEEE Trans. Vis. Comput. Graphics 15 (3) (2009) 383–394.

[86] C. T. Neth, J. L. Souman, D. Engel, U. Kloos, H. Bülthoff, B. J. Mohler, Velocity-dependent dynamic curvature gain for redirected walking, in: Proceedings of Virtual Reality, IEEE, 2011, pp. 151–158.

[87] D. Engel, C. Curio, L. Tcheang, B. Mohler, H. H. Bülthoff, A psychophysically calibrated controller for navigating through large environments in a

limited free-walking space, in: Proceedings of Symposium on Virtual Reality Software and Technology, ACM, 2008, pp. 157–164.

[88] W. H. Warren, D. J. Hannon, Eye movements and optical flow, J. Opt. Soc. Am. A 7 (1) (1990) 160–169.

[89] A. V. van den Berg, Robustness of perception of heading from optic flow, Vis. Res. 32 (7) (1992) 1285–1296.

[90] D. Calow, M. Lappe, Local statistics of retinal optic flow for self-motion through natural sceneries, Network 18 (4) (2007) 343–374.

[91] D. Calow, M. Lappe, Efficient encoding of natural optic flow, Network Comput. Neural Syst. 19 (3) (2008) 183–212.

[92] P. Rößler, U. D. Hanebeck, Simultaneous motion compression for multi-user extended range telepresence, in: Proceedings of the International Conference on Intelligent Robots and Systems, 2006, pp. 5189–5194.

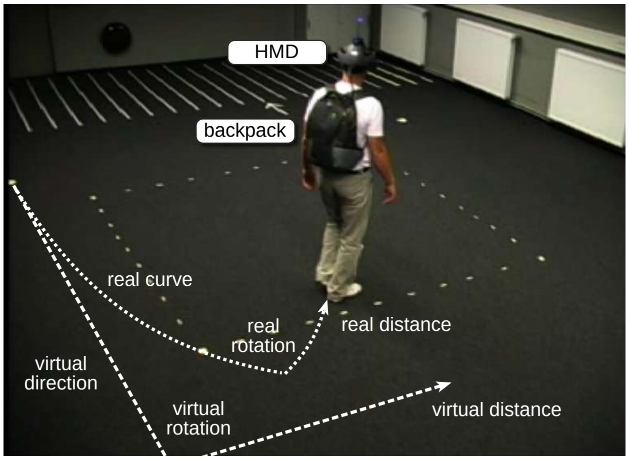
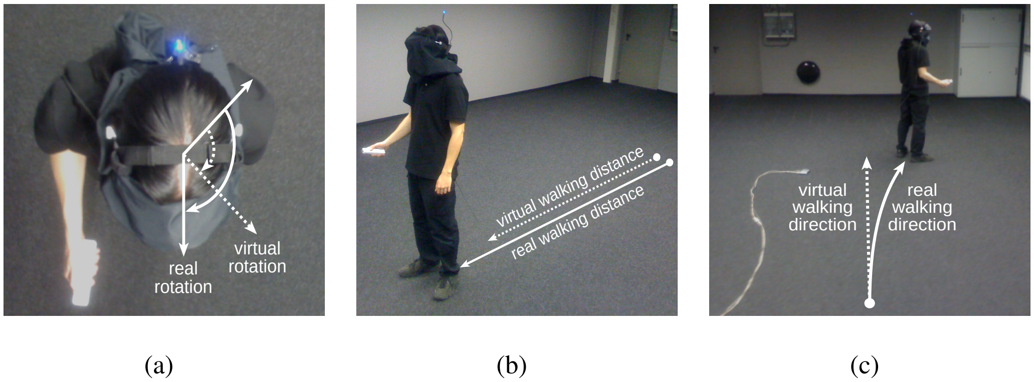
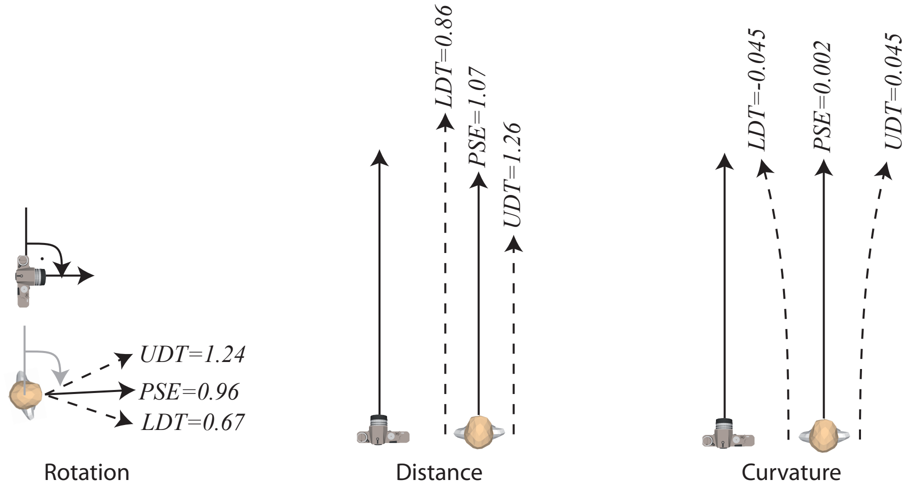


Figure 1: Redirected walking scenario: a user walks in the real world on a different path with a different length in comparison to the path in the virtual world [80].



(a) (b) (c)

Figure 2: Self-motion redirection: (a) discrimination between virtual and physical rotation, (b) discrimination between virtual and physical straightforward movement, and (c) discrimination of path curvature.



(a) (b) (c)

Figure 3: Illustration of the results of the experiment by Steinicke et al. [80] testing self-motion gains using 2AFC tasks: applicable ranges of differences between virtual and physical (a) rotation angles, (b) translation distances, and (c) path curvature.

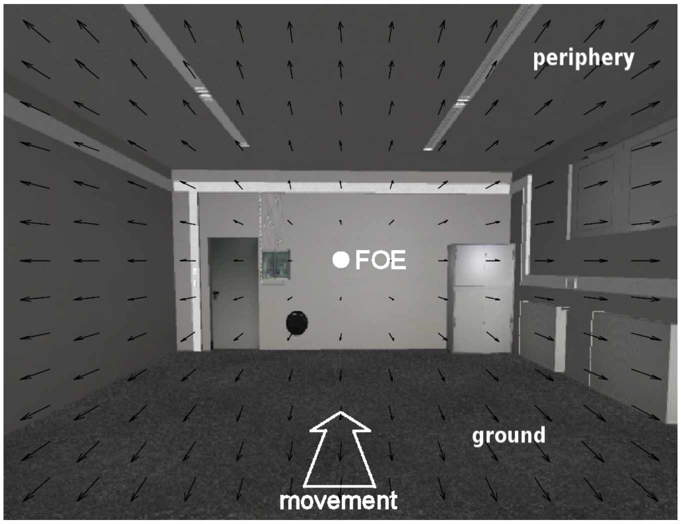
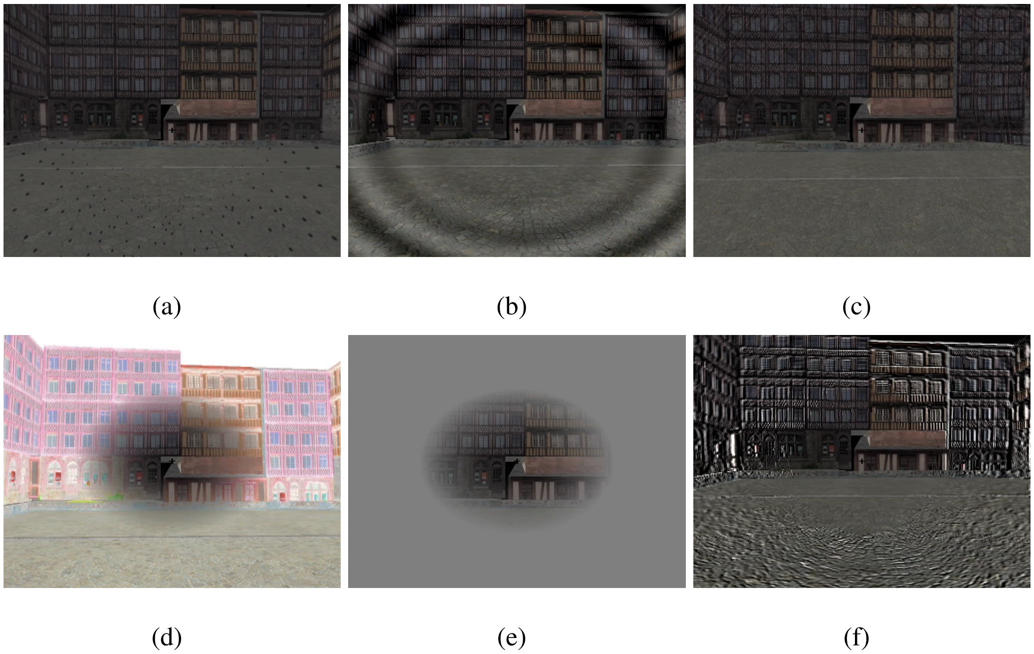


Figure 4: Expansional optic flow patterns with focus of expansion (FOE) for translational movements, peripheral area, and ground plane [38].


(a) (b) (c)

(d) (e) (f)

Figure 5: Illustrations of layered motion with (a) particles, (b) sinus gratings and (c) textures fitted to the scene, as well as (d) contrast inversion, (e) masking and (f) motion without movement. Illusory motion stimuli are limited to peripheral regions.