Analyses of Human Sensitivity to Redirected Walking

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Abstract

Redirected walking allows users to walk through large-scale immersive virtual environments (IVEs) while physically remaining in a reasonably small workspace by intentionally injecting scene motion into the IVE. In a constant stimuli experiment with a two-alternative-forced-choice task we have quantified how much humans can unknowingly be redirected on virtual paths which are different from the paths they actually walk. 18 subjects have been tested in four different experiments: (E1a) discrimination between virtual and physical rotation, (E1b) discrimination between two successive rotations, (E2) discrimination between virtual and physical translation, and discrimination of walking direction (E3a) without and (E3b) with start-up. In experiment E1a subjects performed rotations to which different gains have been applied, and then had to choose whether or not the visually perceived rotation was greater than the physical rotation. In experiment E1b subjects discriminated between two successive rotations where different gains have been applied to the physical rotation. In experiment E2 subjects chose if they thought that the physical walk was longer than the visually perceived scaled travel distance. In experiment E3a subjects walked a straight path in the IVE which was physically bent to the left or to the right, and they estimate the direction of the curvature. In experiment E3a the gain was applied immediately, whereas the gain was applied after a start-up of two meters in experiment E3b. Our results show that users can be turned physically about 68% more or 10% less than the perceived virtual rotation, distances can be up- or down-scaled by 22%, and users can be redirected on an circular arc with a radius greater than 24 meters while they believe they are walking straight.

CR Categories: H.5.1 [INFORMATION INTERFACES AND PRESENTATION]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1 Introduction

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 immersive virtual environments (IVEs) is of great interest for many 3D applications demanding locomotion, such as in urban planning, tourism, or 3D entertainment. Many domains are inherently three-dimensional and advanced visual simulations often provide a good sense of locomotion, but exclusive visual stimuli cannot address the vestibular-proprioceptive system.

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Real walking through IVEs is often not possible [Whitton et al. 2005]. However, an obvious approach is to transfer the user's tracked head movements to changes of the virtual camera in the virtual world by means of a one-to-one mapping. This technique has the drawback that the users' movements are restricted by a limited range of the tracking sensors and a rather small workspace in the real world. Therefore, concepts for virtual locomotion methods are needed that enable walking over large distances in the virtual world while remaining within a relatively small space in the real world. Various prototypes of interface devices have been developed to prevent a displacement in the real world. These devices include torus-shaped omni-directional treadmills [Bouguila and Sato 2002; Bouguila et al. 2002], motion foot pads, robot tiles [Iwata et al. 2006; Iwata et al. 2005] and motion carpets [Schwaiger et al. 2007]. Although these hardware systems represent enormous technological achievements, they are still very expensive and will not be generally accessible in the foreseeable future. Hence there is a tremendous demand for more applicable approaches. As a solution to this challenge, traveling by exploiting walk-like gestures has been proposed in many different variants, giving the user the impression of walking. For example, the walking-in-place approach exploits walk-like gestures to travel through an IVE, while the user remains physically at nearly the same position [Usoh et al. 1999; Schwaiger et al. 2007; Su 2007; Williams et al. 2006; Feasel et al. 2008]. However, real walking has been shown to be a more presence-enhancing locomotion technique than other navigation metaphors [Usoh et al. 1999].

Cognition and perception research suggests that cost-efficient as well as natural alternatives exist. It is known from perceptive psychology that vision often dominates proprioceptive and vestibular sensation when they disagree [Dichgans and Brandt 1978; Berthoz 2000]. When, in perceptual experiments, human participants can use only vision to judge their motion through a virtual scene they can successfully estimate their momentary direction of self-motion but are much less good in perceiving their paths of travel [Lappe et al. 1999; Bertin et al. 2000]. Therefore, since users tend to unwittingly compensate for small inconsistencies during walking it is possible to guide them along paths in the real world which differ from the path perceived in the virtual world. This *redirected walking* enables users to explore a virtual world that is considerably larger than the tracked working space [Razzaque 2005] (see Figure 1).

In this paper we present a series of experiments in which we have quantified how much humans can be redirected without observing inconsistencies between real and virtual motions. The remainder of this paper is structured as follows. Section 2 summarizes previous work related to locomotion and perception in virtual reality (VR) environments. In Section 3 we present a taxonomy of redirected walking techniques as used in the experiments that are described in Section 4. Section 5 summarizes the results and discusses implications for the design of virtual locomotion user interfaces. Finally, we give an overview about future work.

2 Previous Work

Currently locomotion and perception in IVEs are the focus of many research groups analyzing perception in both the real world and virtual worlds. For example, researchers have described that distances in virtual worlds are underestimated in comparison to the real world [Loomis and Knapp 2003; Interrante et al. 2006; Interrante et al. 2007a], that visual speed during walking is underestimated in VEs [Banton et al. 2005] and that the distance one has traveled is also underestimated [Frenz et al. 2007]. Sometimes, users have general difficulties in orienting themselves in virtual worlds [Riecke and Wiener 2007].

From an egocentric perspective the real world appears stationary as we move around or rotate our head and eyes. Both visual and extraretinal cues that come from other parts of the mind or body help us to perceive the world as stable [Wallach 1987; Bridgeman et al. 1994; Wertheim 1994]. Extraretinal cues come from the vestibular system, proprioception, our cognitive model of the world, or from an efference copy of the motor commands that move the respective body parts. When one or more of these cues conflicts with other cues, as is often the case for IVEs (e. g., due to tracking errors or latency) the virtual world may appear to be spatially unstable. Experiments demonstrate that the user tolerates a certain amount of inconsistency between visual and proprioceptive sensation [Steinicke et al. 2008b; Jerald et al. 2008; Peck et al. 2008; Kohli et al. 2005; Burns et al. 2005; Razzaque 2005]. In this context redirected walking [Razzaque 2005] provides a promising solution to the problem of limited tracking space and the challenge of providing users with the ability to explore an IVE by walking. With this approach the user is redirected via manipulations applied to the displayed scene, causing users to unknowingly compensate scene motion by repositioning and/or reorienting themselves.

Different approaches to redirect a user in an IVE have been proposed. An obvious approach is to scale translational movements, for example, to cover a virtual distance that is larger than the distance walked in the physical space. Interrante et al. suggest to apply the scaling exclusively to the main walking direction in order to prevent unintended lateral shifts [Interrante et al. 2007b]. With most reorientation techniques, the virtual world is imperceptibly rotated around the center of a stationary user until he/she is oriented in such a way that no physical obstacles are in front of him/her [Peck et al. 2008; Razzaque 2005; Kohli et al. 2005]. Then, the user can continue to walk in the desired virtual direction. Alternatively, reorientation can also be applied while the user walks [Groenda et al. 2005; Steinicke et al. 2008b; Razzaque 2005]. For instance, if the user wants to walk straight ahead for a long distance in the virtual world, small rotations of the camera redirect him/her to walk unconsciously on an arc in the opposite direction in the real world. When redirecting a user, the visual sensation is consistent with motion in the IVE, but proprioceptive sensation reflects motion in the physical world. However, if the induced manipulations are small enough, the user has the impression of being able to walk in the virtual world in any direction without restrictions.

Redirection techniques have been applied particularly in robotics for controlling a remote robot by walking [Groenda et al. 2005]. For such scenarios much effort has been undertaken to prevent collisions–sophisticated path prediction is therefore essential [Groenda et al. 2005; Nitzsche et al. 2004]. These techniques guide users on physical paths for which lengths as well as turning angles of the visually perceived paths are maintained, but the user observes the discrepancy between both worlds.

Until now not much research has been undertaken in order to identify thresholds which indicate the tolerable amount of deviation between vision and proprioception while the user is moving. Preliminary studies [Steinicke et al. 2008b; Peck et al. 2008; Razzaque 2005] have shown that in general redirected walking works as long as the subjects are not focused on detecting the manipulation. In these experiments user had to remark afterwards, if they noticed a manipulation or not. Quantified analyzes have not been undertaken. Some work has been done in order to identify thresholds for detecting scene motion during head rotation [Wallach 1987; Jerald et al. 2008], but walking was not considered in these experiments.

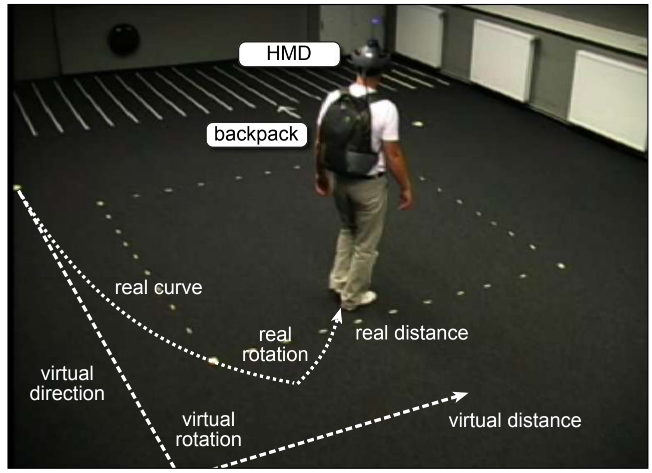

Figure 1: *Redirected walking scenario: a user walks in the real environment on a different path with a different length in comparison to the perceptual path in the virtual world.*

In summary, substantial efforts have been made to allow a user to walk through a large-scale VE, but this challenge has not yet been addressed adequately.

3 Generalized Redirected Walking

Redirected walking can be implemented using gains which define how tracked real-world motions are mapped to the VE. These gains are specified with respect to a coordinate system. For example, they can be defined by uniform scaling factors that are applied to the virtual world registered with the tracking coordinate system such that all motions are scaled likewise.

3.1 Human Locomotion Triple

In [Steinicke et al. 2008a] we have introduced the *human locomotion triple (HLT)* (s, u, w) by three normalized vectors, i. e., strafe vector s, up vector u and direction of walk w. The user's direction of walk can be determined by the actual walking direction or using proprioceptive cues such as the orientation of the limbs or the view direction. In our experiments we define w by the actual walking direction tracked and filtered by the tracking system. The strafe vector, a.k.a. *right vector*, is orthogonal to the direction of walk and parallel to the walk plane. Whereas the direction of walk and the strafe vector are orthogonal to each other, the up vector u is not constrained to the crossproduct of s and w. Hence, if a user walks up a slope the direction of walk is defined according to the walk plane's orientation, whereas the up vector is not orthogonal to this tilted plane. When walking on slopes humans tend to lean forward, so the up vector is invers to the direction of gravity. As long as the direction of walk holds $w \neq (0, 1, 0)$, the HLT composes a coordinate system. In the following sections we describe how gains can be applied to such a locomotion triple. We define u by the up vector of the tracked head orientation.

3.2 Translation gains

Assume that the tracking system detects a change of the user's real world position defined by the vector $T_{\text{real}} = P_{\text{cur}} - P_{\text{pre}}$, where P_{cur} is the current position and P_{pre} is the previous position, T_{real} is mapped one-to-one to the virtual camera with respect to the registration between virtual scene and tracking coordinates system. A translation gain $g_T \in \mathbb{R}^3$ is defined for each component of the HLT (see Section 3.1) by the quotient of the mapped virtual world translation T_{virtual} and the tracked real world translation T_{real}, i. e., $g_T := \frac{T_{\text{virtual}}}{T_{\text{real}}}$. Hence, generic gains for translational movements can be expressed by $g_{T[s]}, g_{T[u]}, g_{T[w]}$, where each component is applied to the corresponding vector s, u and w respectively composing the translation. In our experiments we have focussed on sensitivity to translation gains $g_{T[w]}$.

3.3 Rotation gains

Real-world head rotations can be specified by a vector consisting of three angles, i. e., $R_{\text{real}} := (pitch_{\text{real}}, yaw_{\text{real}}, roll_{\text{real}})$. The tracked orientation change is applied to the virtual camera. Analogous to Section 3.2, rotation gains are defined for each component (pitch/yaw/roll) of the rotation and are applied to the axes of the locomotion triple. A rotation gain g_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 virtual scene appears to move against the direction of the head turn, whereas a gain $g_R < 1$ causes the scene to rotate in the direction of the head turn. Rotation gains can be expressed by $g_{R[s]}, g_{R[u]}, g_{R[w]}$, where the gain $g_{R[s]}$ specified for pitch is applied to s, the gain $g_{R[u]}$ specified for yaw is applied to u, and $g_{R[w]}$ specified for roll is applied to w. In our experiments we have focussed on rotation gains for yaw rotation $g_{R[u]}$.

3.4 Curvature gains

Instead of multiplying gains with translations or rotations, offsets can be added to real world movements. Thereby, camera manipulations are enforced if only one kind of motion is tracked, for example, user turns the head, but stands still, or the user moves straight without head rotations. If the injected manipulations are reasonably small, the user will unknowingly compensate for these offsets resulting in walking a curve. The gains can be applied in order to inject rotations, while users virtually walk straight, or gains can be applied, while users only rotate their heads. The curvature gain g_C denotes the resulting bend of a real path. For example, when the user moves straight ahead, a curvature gain that causes reasonably small iterative camera rotations to one side enforces the user to walk along a curve in the opposite direction in order to stay on a straight path in the virtual world. The curve is determined by a circular arc with radius r, and $g_C := \frac{1}{r}$. 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 $\frac{\pi}{2}$ meters the user has covered a quarter circle with radius $r = 1 \Rightarrow g_C = 1$.

Alternatively, gains can be applied as translation offsets while the user turns the head and no translational movements are intended. While the user turns, such a gain causes the camera to shift to one direction such that the user will unknowingly move to the opposite direction in order to compensate an unintended displacement in the virtual world. Potentially, such gains can be applied to each axes of the HLT. However, in our experiments we focussed on the common procedure which enforce users to walk on an arc parallel to the walk plane by means of curvature gains $g_{C[w]}$. Furthermore, gains can be applied time-dependantly, but this appraoch is not in the scope of this paper.

4 Experiments

In this section we present five experiments in which we have quantified how much humans can unknowingly be redirected. We have analyzed the appliance of translation $g_{T[w]}$, rotation $g_{R[u]}$, and curvature gains $g_{C[w]}$.

4.1 Experimental Design

Since the main objective of our experiments is to allow users to walk unlimitedly in 3D city environments, the visual stimulus consisted of virtual scenes of the city of Münster in Germany (see Figure 2). Before each trial a random place and a horizontal gaze direction were chosen. The only restriction for this starting scene was that no vertical objects were within $10m$ of the starting position in order to prevent collisions in the VE.

We performed all experiments in a $10 \times 10m$ darkened laboratory room. The subjects wore an HMD (3DVisor Z800, 800x600@60 Hz, 40° diagonal field of view (FoV)) for the stimulus presentation. On top of the HMD an infrared LED was fixed. We tracked the position of this LED within the room with an active optical tracking system (Precise Position Tracking of World Viz), which provides submillimeter precision and sub-centimeter accuracy. The update rate was 60 Hz providing real-time positional data of the active markers. For three degrees of freedom (DoF) orientation tracking we used an InertiaCube 2 (InterSense) with an update rate of 180 Hz. The InertiaCube was also fixed on top of the HMD. In the experiments we used an Intel computer (host) with dual-core processors, 4 GB of main memory and an *n*Vidia GeForce 8800 for system control and logging purposes.

Participants were equipped with an HMD backpack consisting of a laptop PC with a GeForce 7700 Go graphics card (see Figure 1). The scene was rendered using OpenGL and our own software with

Figure 2: *Example scene from Virtual Münster as used for the experiments E1a, E1b, and E2. In experiment E3 a pave on which subjects had to walk was added to the scene. No obstacles are within a $10m$ distance from the user.*

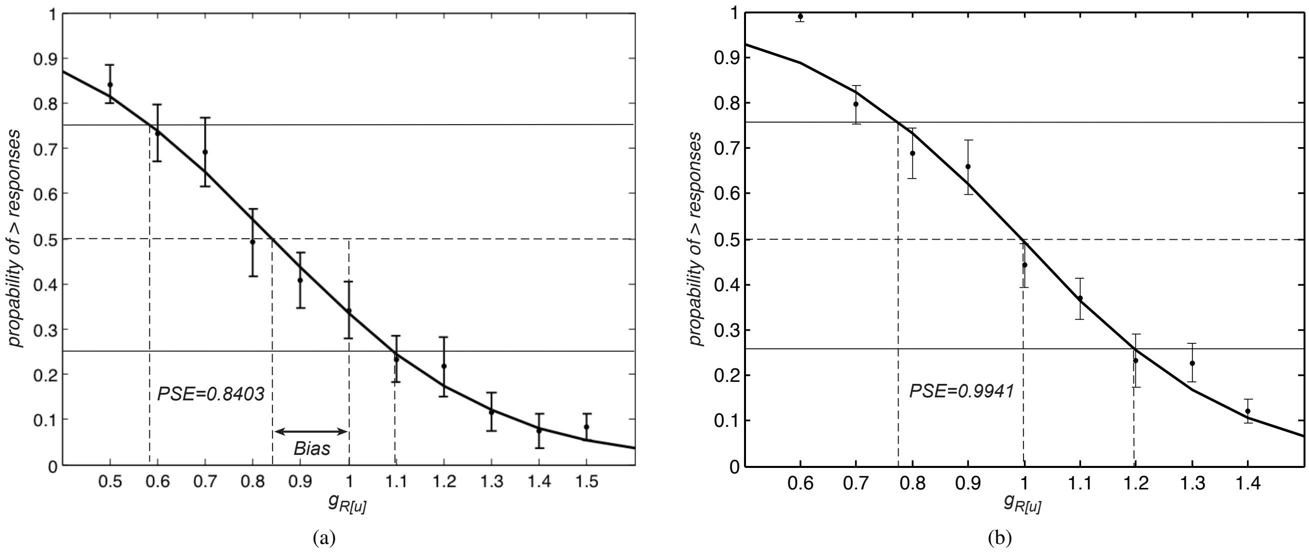

Figure 3: *Pooled results of the discrimination between (a) virtual and physical rotation and (b) two successive rotations. In (a) the x-axis shows the applied rotation gain $g_{R[u]}$, the y-axis shows the probability of estimation a physical rotation greater than the virtual counterpart. Figure (b) shows the pooled results of the discrimination between two successive rotations. The x-axis shows again the rotation gain $g_{R[u]}$ applied to one of the both rotations, the y-axis shows the probability that subjects estimated the manipulated rotation greater than the non-manipulated one.*

which the system maintained a frame rate of 60 frames per second. The latency for the entire system was approximately $45ms$ on average. During the experiment the room was entirely darkened in order to reduce the user's perception of the real world. The subjects received instructions on slides presented on the HMD. A Nintendo WII remote controller served as input device.

All computers, including the laptop on the back of the user, were equipped with wireless LAN adapters. The entire weight of the backpack is about 8 kg which is quite heavy. However, no wires disturb the immersion and no assistant must walk beside the user to keep an eye on the wires. Sensing the wires would give subjects a cue to orient physically, an issue we had to avoid in our experiments. In order to focus subjects on the tasks no communication between observer and subject was performed during the experiment. All instructions were displayed in the VE, and subjects responded via the WII device. Acoustic feedback was used for ambient city noise in the experiment such that an orientation by means of auditory feedback in the real world was not possible.

15 male and 3 female (age 24-35, $\varnothing$: 27.3) subjects participated in the entire experiment. Subjects came from backgrounds ranging from students to professionals with expertise in computer science, mathematics, psychology, geoinformatics, and physics. All had normal or corrected to normal vision; 4 wear glasses or contact lenses. 3 had no game experience, 10 had some, and 4 had much game experience. Three of the authors served as subjects; all other subjects were naïve to the experimental conditions. 8 of them had experience with walking in VR environments using an HMD setup. Subjects were allowed to take breaks at any time. Some subjects obtained class credit for their participation. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks, and debriefing took 3 hours.

For all experiments we used the method of constant stimuli in a *two-alternative forced-choice* (2AFC) task. In the method of constant stimului, the applied gains are not related from one trial to the next, but presented randomly and uniformly distributed. The subject choses between one of two possible responses, e. g. "Was the physical movement greater than virtual movement: yes or no"; responds like "I can't tell." were not allowed. In this version, when the subject cannot detect the signal, he/she must guess, and will be correct on average in 50% of the trials. The gain at which the subject responds "greater" in 50% of the trials is taken as the *point of subjective equality* (PSE), at which the subject perceives 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. In this paper we rather focus on the range of gains over which the subject cannot reliably detect the difference than the gain at which subjects perceive physical and virtual movement as identical.

We define the *detection threshold* (DTs) for gains larger than the PSE to be the value of the gain at which the subject has 75% probability of choosing the "greater" response correctly and the detection threshold for gains smaller than the PSE to be the value of the gain at which the subject chooses the "yes, greater" response in only 25% of trials (since the correct response "no" was then chosen in 75% of the trails).

4.2 Experiment 1a (E1a): Discrimination between virtual and physical rotation

In this experiment we investigated subject's ability to discriminate whether a physical rotation was greater than the simulated virtual rotation (see Section 3.3). Therefore, we instructed the subjects to rotate on a physical spot and we mapped this rotation to a corresponding virtual rotation to which different gains had been applied.

4.2.1 Material and Methods for E1a

At the beginning of each trial the virtual scene was presented on the HMD together with the written instruction to physically turn right or left until a red dot drawn at eye height was directly in front of the subject's gaze direction. The subjects indicated the end of the turn with a button press on the WII controller. Afterwards the subjects had to decide whether the physical rotation was greater (right button) or not greater (left button) than the visually simulated rotation in a 2AFC task. Before the next trial started, subjects had to turn to a new orientation. We indicated the reorientation process in the IVE setup by a white screen and two orientation markers (current orientation and target orientation). We implemented this rotation to prevent adaptation of the subjects to the scene. The virtual rotation was always 90° either to the right or left of the starting orientation. We varied the gain $g_{R[u]}$ between the physical and virtual rotation randomly in the range between 0.5 (180° physical rotation resulted in a 90° virtual rotation) and 1.5 (60° physical rotation resulted in a 90° virtual rotation) in steps of 0.1. We tested each gain 10 times in randomized order. 12 subjects participated in this experiment.

4.2.2 Results of E1a

Figure 3 (a) shows the mean detection rates together with the standard error over all subjects for the tested gains. The x-axis shows the applied rotation gain $g_{R[u]}$, the y-axis shows the probability for estimating a physical rotation greater than the mapped virtual rotation. The solid line shows the fitted sigmoid function of the form $f(x) = \frac{1}{1+e^{a \cdot x+b}}$ with real numbers a and b. We found no dependency whether we simulated the rotation to the left or right and therefore pooled the two conditions. Using the sigmoid function we determined a bias for the point of subjective equality resulting in a $PSE = 0.8403$. For individual subjects, we found the PSE to vary between 0.54 and 1.24 (2 subjects with PSE greater than 1.0, the rest less than 1.0). Detection thresholds were at gains of 0.59 for greater responses and at 1.1 for not greater responses, suggesting that gain differences within this range cannot be reliably estimated, i. e., subjects have serious problems to discriminate between a 90° virtual and real rotations ranging from 81° and 152°. Hence, subjects can be turned physically about 68% more or 10% less than the perceived virtual rotation.

4.2.3 Discussion

The results show that subjects underestimate a physical 90° rotation about 16% compared to the rotation in the virtual world. According to the experiments in [Jerald et al. 2008] we assumed an asymmetric psychometric function, which could be reproduced in our experiment, and we observed a bias for the mean PSE. The asymmetry implies that a gain $g_{R[u]} < 1$ downscaling a physical rotation is less noticeable for the subjects. In this case the scene seems to move slightly with the head rotation as shown in previous research [Jerald et al. 2008]. The bias for the PSE means that subjects estimated a virtual rotation scaled with a gain $g_{R[u]} = 0.8403$ identical to the physical rotation. With such a gain users have to rotate by more than 107° in order to achieve a 90° virtual rotation. One reason for this shift could be that a subject's estimation was based on the question of whether the physical rotation was greater or not. Since "or not" has an ambiguous possibly meaning equal or smaller, in the case that subjects estimated both as equal they answer in the negative, giving a bias to the left. Although, we are rather focussed on the range of gains over which subjects cannot reliably detect the difference than the individual gain at which subjects perceive physical and virtual movement as identical we performed a second experiment in order to further analyze this phenomenon.

4.3 Experiment 1b: Discrimination between two succesive rotations

Here, we examined the human's ability to discriminate between two successive rotations in the physical and virtual world.

4.3.1 Material and Methods for E1b

The experimental setup was very similar to that of experiment 1a. At the start of each trial a written instruction was visible in the virtual scene prompting the subject to turn to the left or the right. The end of the first 90° rotation was reached when a red dot drawn at eye height was directly in front of the subject. Afterwards the subjects had to turn back to the starting orientation, which was also indicated by a virtual red dot. Alternately, we simulated one of the both rotations with a gain $g_{R[u]} = 1.0$ between physical and virtual rotation (both 90°), whereas the other rotation was simulated with different gains ranging between 0.6 and 1.4 in steps of 0.1. Each gain was tested 8 times in a randomized order. 11 subjects participated in this experiment.

4.3.2 Results of E1b

One subject had to be excluded from the experiment due to cybersickness (see Section 5). Figure 3 (b) shows the results of the discrimination experiment. Response means with standard errors over all subjects are plotted for the tested gains. While for one rotation the gain satisfied $g_{R[u]} = 1.0$, the x-axis shows the gain $g_{R[u]}$ applied to the other rotation. The y-axis shows the probability that subjects estimated the manipulated physical rotation greater than the non-manipulated physical rotation. The solid line shows the same fitted sigmoid function as used in experiment E1a. In this experiment the mean PSE approximates 0.9941. For the single subjects we found PSE values varying between 0.7 and 1.19 (5 subjects with PSE equal or above 0.9941, the rest less than 0.9941). Detection thresholds were at gains of 0.76 for greater responses and at 1.19 for not greater responses.

4.3.3 Discussion

Subjects cannot discriminate between rotation gains that deviate by 24% downwards and 19% upwards from a $g_{R[u]} = 1.0$, i. e., physical rotations between 68° and 107° cannot be discriminated from a 90° rotation. We could not find any impact of the sequence of both rotations for the estimation, but rotation gains have to be conducted in further studies.

In summary both experiments show that subjects had serious problems discriminating rotations. Subjects can be redirected sufficiently via reorientation techniques based on rotation gains.

4.4 Experiment 2 (E2): Discrimination between virtual and physical translational movement

In this experiment we analyzed the ability to discriminate between virtual and physical translational movements (see Section 3.2). The virtual movement was a forward movement mapped to physical walking.

4.4.1 Material and Methods for E2

In the IVE subjects always had to walk a distance of $5m$. The walking direction was indicated by a green dot in front of the subjects (see Figure 2). When the subjects travelled $5m$ in the virtual scene, the dot turned red to indicate the end of the distance. The dot was constant in size and positioned on the subject's eye level above the ground. The physical distance the subjects had to walk varied between $3m$ and $7m$, i. e., gain $g_{T[w]}$ was between 0.6 and 1.4 in steps of 0.1. We presented the gains each 8 times in a randomized order. The task was to judge whether the physical walking distance was larger than the virtual travel distance or not. After each trial the subject had to walk back to the starting position, guided by two reference markers on an otherwise white screen. One marker showed the actual position of the subject relative to the second fixed marker, which represented the starting position. 16 subjects participated in this experiment.

4.4.2 Results of E2

In Figure 4 we plotted the mean probability for a subject's estimation that the physical distance was larger than the virtual perceived one over all subjects against the tested gains. The error bars show the standard errors. A translation gain $g_{T[w]}$ which satisfies $g_{T[w]} < 1$ resulted in a larger physical walking distance compared to the virtual distance, a gain $g_{T[w]} > 1$ resulted in a smaller physical walking distance compared to the virtual distance. We fitted the data with the same sigmoidal function as in experiments E1a and E1b. We dismissed the data set of two subjects from further analyse. One subject always indicated that the physical walking distance is larger than the virtual distance. The second subject either mixed up the answer buttons or misunderstood the task. The PSE for the pooled data of the remaining 14 subjects is 0.9972. This means the subjects are very accurate in discriminating the walking distance in the physical and virtual world. The calculated PSE for the single subjects varied between 0.78 and 1.19 (7 subjects with PSE above or equal 0.9972, the rest less than 0.9972). DTs for estimation of translational movements are given for gains at 0.78 for greater responses and at 1.22 for not greater responses.

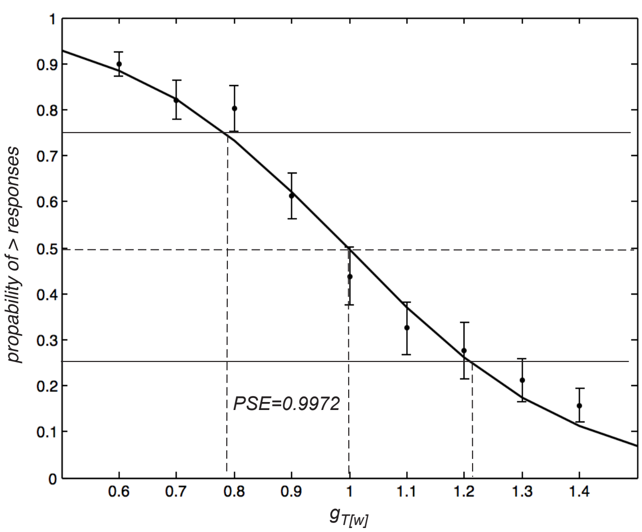

Figure 4: *Pooled results of the discrimination between virtual and physical translational movement. The x-axis shows the applied translation gain $g_{T[w]}$, the y-axis shows the probability that subjects estimate the physical translational movement greater than the mapped virtual motion.*

4.4.3 Discussion

The results indicate that human can discriminate between virtual and real translational movements accurately when actually walking a distance in a familiar environment such as realistic 3D city model. However, since the estimation was based on the question wether physical movements were "greater" or "not greater" again, a bias as described in Section 4.2) might be included also in the results for this experiment. This means that the actual PSE has been shifted again.

Since subjects knew the VE from the real world, they were able to exploit distance cues such as the height of trees, street sizes etc. As stated in [Interrante et al. 2007b] such cues rather support subjects when estimating distances in comparison to evaluate features in artificial environments without walking.

4.5 Experiment 3a (E3a): Discrimination of direction of walk

In this experiment we analyze sensitivity to curvature gains which enforce the user to walk on a curve in order to stay on straight path (see Section 3.4).

4.5.1 Material and Methods for E3a

To support users to virtually walk on a straight path we introduced a $1m$ wide pavement. In level with the subject's eye height we added a green dot in the scene, which turned red when the subjects had walked $5m$ towards it. While the subjects walked along the pavement, we rotated the scene to either side with a velocity linked to the subject's movement velocity. The scene rotated by approximately $0, 5, 10, 20$ and 30 degrees after $5m$ walking distance. This corresponds to a curvature radius of approximately ∞, 57.3, 28.65, 14.32 and $9.55m$ respectively. The rotation started immediately when they began to walk. After the subjects walked a distance of $5m$ in the virtual world, the screen turned white and the written instruction appeared. The subject's task was to decide whether the physical path was curved to the left or not by pressing a button on the WII controler. To guide the subjects back to the starting position we used the two markers on an otherwise white screen again. 10 subjects participated in this experiment.

4.5.2 Results of E3a

In Figure 5 we plotted the mean probability for a subject's estimation that the physical path was curved to the left against the curvature gains $g_{C[w]}$ (black symbols). The variance is the standard error. The DTs is the stimulus intensity at which subjects correctly detect the stimulus 75% of the time. In this experiment the detection thresholds are given by $g_{C[w]} = -\frac{\pi}{50}$ and $g_{C[w]} = +\frac{\pi}{52.94}$ respectively. We found no statistical significant difference whether we simulated a curvature to the left or right. The slight bias might be introduced due to the question as described above. The PSE for the pooled data is $-\frac{\pi}{517} = -1.74$.

4.5.3 Discussion

The results show that subjects can be reoriented by 18° to the left or 17° to the right after $5m$ of walking, which corresponds to walking along a circular arc with a radius of approximately 16 meters. We applied the curvature gain during the entire walk during this experiment. Subjects reported that they had difficulty estimating the direction of the bending particularly during the first steps. For instance, after two gaits, they left the pavement and had to reorient themselves to the target and continue the walk. Consequently, they tend to walk in a triangle rather than walking on an arc.

4.6 Experiment 3b (E3b): Discrimination of walking direction, part 2

Due to the subjects' uncertainty we modified the conditions of experiment E3a. We introduced a $2m$ travel distance without scene manipulation before the curvature gain $g_{C[w]}$ was applied.

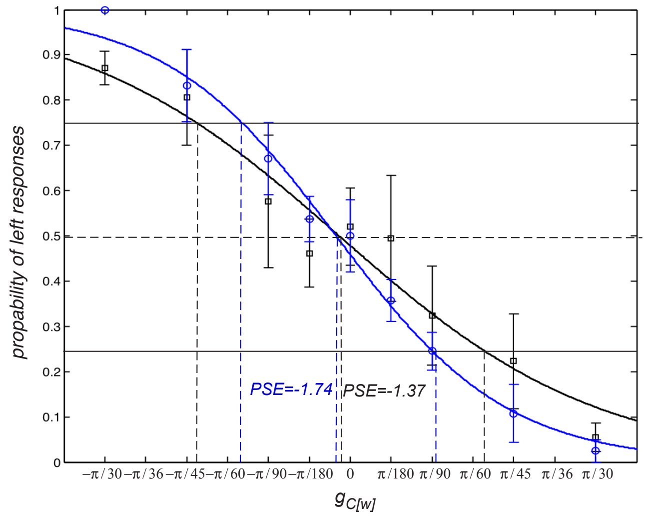

Figure 5: *Pooled results of the discrimination of the direction of walk. The x-axis shows the applied curvature gain which bends the walked path either to the left ($g_{C[w]} < 0$) or the right ($g_{C[w]} > 0$), the y-axis shows the portion of subjects' left detections of the bending.*

4.6.1 Material and Methods for E3b

We used the same experimental setup as in experiment 3a. The only difference was an additional $2m$ start-up travel distance without any scene manipulation. Again, the scene rotated by approximately $0, 5, 10, 20$ and 30 degrees after the $7m$ walking distance, from which the last $5m$ have been curved with corresponding curvature gains $g_{C[w]} = \{0, \frac{\pi}{180}, \frac{\pi}{90}, \frac{\pi}{45}, \frac{\pi}{30}\}$. Afterwards the subjects decided again whether the physical walking path was curved to the left or not. The same 10 subjects which have participated already in experiment E3a were tested in this condition.

4.6.2 Results of E3b

The results are plotted in Figure 5 (blue symbols). The error bars are the standard errors. Also in this condition we found no significant difference whether we performed a camera rotation to the left or right. The PSE for the pooled data is $-\frac{\pi}{657} = -1.37$. In this experiment the detection thresholds shifted to gains $g_{C[w]} = -\frac{\pi}{69.23}$ for left and $g_{C[w]} = +\frac{\pi}{85.71}$ for right curvatures respectively. Until this DT subjects cannot estimate reliably if they walk straight or on a curve.

4.6.3 Discussion

Subjects are significantly more sensitive to the bending compared to the condition in the previous experiment. With this condition subjects can be reoriented by $13°$ to the left or $10.5°$ to the right after $5m$ walking without noticing the discrepancy between real and virtual motion. This corresponds to walking along a circular arc with a radius of approximately 24 meters. When redirected walking is applied this is a typical situation where users first walk a certain distance before the path is curved.

5 Conclusions and Future Work

In this paper, we analyzed the users' sensitivity to redirected walking manipulations in several experiments. We introduced a taxonomy of redirection techniques and tested the corresponding gains in a practical useful range for their perceptibility. The results of the conducted experiments show that users can be turned physically about 68% more or 10% less than the perceived virtual rotation without noticing the difference.

Our results agree with previous findings [Jerald et al. 2008] that users are more sensitive to scene motion if the scene moves against head rotation than if the scene moves with head rotation. Walked distances can be up- and down-scaled by 22%. When applying curvature gains users can be redirected such that they unknowingly walk on a circular arc when the radius is greater or equal to 24 meters. Certainly, redirected walking is a subjective matter, but the results have potential to serve as thresholds for the development of future locomotion interfaces.

We have performed further questionnaires in order to determine the users' fear of colliding with physical objects. The subjects revealed their level of fear on a four point Liker-scale (0 corresponds to no fear, 4 corresponds to a high level of fear). On average the evaluation approximates 0.6 which shows that the subjects felt safe even though they were wearing an HMD and knew that they were being manipulated. Further post-questionnaires based on a comparable Likert-scale show that the subjects only had marginal positional and orientational indications due to environmental audio (0.6), visible (0.1) or haptic (1.6) cues. We measured simulator sickness by means of Kennedy's Simulator Sickness Questionnaire (SSQ). The Pre-SSQ score averages for all subjects to 16.3 and the Post-SSQ score to 36.0. For subjects with high Post-SSQ scores, we conducted a follow-up test on another day to identify whether the sickness was caused by the applied redirected walking manipulations. In this test the subjects were allowed to walk in the same IVE for a longer period of time while this time no manipulations were applied. Each subject who was susceptible to cybersickness in the main experiment, showed the same symptoms again after approximately 15 minutes. Although cybersickness is an important concern, the follow-up tests suggest redirected walking does not seem to be a large contributing factor of cybersickness.

The findings include detection thresholds, which have essential implications for the design of future locomotion user interfaces, that are based on redirected walking. Our virtual locomotion interface is adapted to the results of the experiments. In the future we will consider other redirection techniques presented in the taxonomy of Section 2, which have not been analyzed in the scope of this paper. Moreover, further conditions have to be taken into account and tested for their influence on redirected walking, for example, distances of scene objects, level of detail, contrast, etc. Informal tests have motivated that manipulations can be intensified in some cases, e. g., when less objects are close to the camera, which could provide further motions cues while the user walks.

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