Reorientation during Body Turns

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Abstract

Immersive virtual environment (IVE) systems allow users to control their virtual viewpoint by moving their tracked head and by walking through the real world, but usually the virtual space which can be explored by walking is restricted to the size of the tracked space of the laboratory. However, as the user approaches an edge of the tracked walking area, reorientation techniques can be applied to imperceptibly turn the user by manipulating the mapping between real-world body turns and virtual camera rotations. With such reorientation techniques, users can walk through large-scale IVEs while physically remaining in a reasonably small workspace.

In psychophysical experiments we have quantified how much users can unknowingly be reoriented during body turns. We tested 18 subjects in two different experiments. First, in a just-noticeable difference test subjects had to perform two successive body turns between which they had to discriminate. In the second experiment subjects performed body turns that were mapped to different virtual camera rotations. Subjects had to estimate whether the visually perceived rotation was slower or faster than the physical rotation. Our results show that the detection thresholds for reorientation as well as the point of subjective equality between real movement and visual stimuli depend on the virtual rotation angle.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [INFORMATION INTERFACES AND PRE-SENTAION]: Multimedia Information Systems—Artificial, augmented, and virtual realities I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1. Introduction

Walking is the most basic and intuitive way of moving within the real world. While moving in the real world, 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 motion, i. e., acceleration, speed and direction of travel. However, in IVEs, which are often characterized by head-mounted displays (HMDs) and a tracking system, a realistic simulation of locomotion techniques as used in the real world, e. g., walking and running, is difficult to implement [WCF*05]. An obvious approach to support real walking in IVEs 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. Using this technique a one meter movement in the real world is mapped to a one meter movement of the virtual camera in the corresponding direction in the VE and a 90° real-world body turn is mapped to a 90° virtual cam-

era rotation. 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. Since the size of the virtual world often differs from the size of the tracked laboratory space, a straightforward implementation of omni-directional and unlimited walking is not possible. Thus, 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. As one solution to this challenge, traveling by exploiting walk-like gestures has been proposed in many different variants, giving a user the impression of walking [FWW08]. However, real walking has been shown to be a more presence-enhancing locomotion technique than walking-in-place approaches [UAW*99]. Various other approaches and proto-types of interface devices based on sophisticated hardware have been developed to prevent a displacement in the real world [IHT06]. Although these hardware systems represent

significant technological achievements, they are still very expensive and will not be generally accessible in the foreseeable future.

Cognition and perception research suggests that cost-efficient as well as natural alternatives exist. It is known from perceptive psychology that vision often dominates proprioception and vestibular sensation if they disagree [Ber00, DB78]. In perceptual experiments in which 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 capable of perceiving their paths of travel [BIL00, LBvdB99]. Therefore, since users tend to unwittingly compensate for small inconsistencies during moving, it is possible to guide them along paths in the real world which differ from the paths perceived in the virtual world. This *redirected walking* enables users to explore a virtual world that is considerably larger than the tracked working space [Raz05]. Although it has been shown that redirected walking works in general, there are situations in which the technique fails and the user comes close to leaving the tracked space or is about to collide with an obstacle. In such a situation *reorientation techniques* must stop the user and rotate the VE around her current virtual location, e. g., while instructing her to turn in the real world. With these techniques the user is turned around in the real environment so that she can follow her desired path in the newly-rotated VE without colliding with obstacles in the real world.

In this paper we present two experiments in which we have quantified how much humans can be reoriented without observing inconsistencies between real and virtual body turns. In the first experiment subjects had to discriminate between two successive body turns. In the second experiment they had to discriminate between real and virtual rotations. In both experiments we tested different virtual rotation angles for their impact on perceptibility of manipulations. The remainder of this paper is structured as follows. Section 2 summarizes previous work related to perception and reorientation in VR-based environments. Section 3 explains how reorientation techniques are applied to body turns. Section 4 describes the psychophysical experiments and reports the results. Section 5 discusses the results. Section 6 concludes the work and gives an overview about future work.

2. Related Work

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 and body help us perceive the world as stable [BvdHV94, Wal87, Wer94]. 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. In case one or more of these cues conflict 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 users tolerate a certain amount of inconsistency between visual and proprioceptive sensation in IVEs [BRP*05, JPSW08, Raz05, PWF08, JAH*02].

Redirected walking and reorientation techniques provide a promising solution to the problem of limited tracking space and the challenge of providing users with the ability to explore a virtual world by walking [Raz05, PWF08]. Different approaches to redirect a user in an IVE have been proposed. One approach is to scale translational movements, for example, to cover a virtual distance that is larger than the distance walked in the physical space [IRA07, WNM*06]. With most reorientation techniques, the virtual world is imperceptibly rotated around the center of a user with or against the direction of active head turns, until she is oriented in such a way that no physical obstacles are in front of her [PWF08, Raz05]. Then the user can continue to walk in the desired virtual direction. Alternatively, reorientation can also be applied while the user walks [GNRH05, Raz05]. For instance, if the user wants to walk straight ahead for a long distance in the virtual world, small rotations of the camera redirect her to walk unconsciously on an arc in the opposite direction in the real world. In case of reorienting a user, the visual sensation is consistent with motion in the IVE, but proprioceptive sensation reflects motion in the physical world.

Until recently, hardly any 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, in particular during rotations. Preliminary studies have shown that in general reorientation works [Raz05, PWF08]. Some work has been done in order to identify thresholds for detecting scene motion during head rotation [JPSW08, Wal87, JAH*02], but active body turns were not considered in these experiments. Recently, first psychophysical studies have identified detection thresholds for reorientation gains. For example, Steinicke et al. [SBJ*09] have performed discrimination tasks similar to one experiment presented in this paper (cf. Section 4.3) The results suggest that users can be turned imperceptibly about 49% more or 20% less in the real world than the perceived virtual rotation. However, in their experiment the tests were always restricted to a 90° virtual rotation, which was mapped to different physical rotations. In their work the authors make the assumption that the derived detection thresholds could be generalized and applied also to body turns with other virtual rotation angles.

3. Reorientation Techniques

Different methods have been proposed to manipulate the VE in the situation that the user approaches an edge of the tracked walking area or comes close to colliding with a physical obstacle. One technique involves turning the HMD off,

instructing the user to walk backwards to the middle of the lab and then turning the HMD back on [WNR*06]. Then, the user will find herself in the same place in the VE, but will no longer be close to an edge of the tracked space. Another technique turns the HMD off, asks the user to rotate in place, and then turns the HMD back on [WNR*06]. The user will then find herself facing the same direction in the VE, but will face a different direction in the tracked space. Both approaches have the main drawback that users experience a break in presence when the HMD is turned off. Therefore, Razzaque et al. suggest a method involving a sound in the VE that asks the user to stop, turn her head back and forth, e. g., towards markers displayed as insets in the virtual scene, and continue walking in the same virtual direction, while applied *rotation gains* have imperceptibly reoriented the user during the rotations in the real world [Raz05]. Peck et al. enhanced this approach with visual "distractors", i. e., objects displayed in the virtual world, which the user has to follow by turning her head and body until she can continue walking [PWF08]. Both of these approaches allow to imperceptibly reorient users in the real world in case that only small manipulations are applied. However, for large reorientation angles such as $180°$ it is important to imperceptibly turn a user in the real world as much as possible as fast as possible. Therefore, it is important to evaluate how much discrepancy between real and virtual rotations a user cannot detect for different virtual rotation angles.

Assuming that the user's head is tracked, such reorientation during a body turn can be expressed as follows. Real-world rotations can be specified by a vector consisting of three angles, i. e., $R_{\text{real}} := (pitch_{\text{real}}, yaw_{\text{real}}, roll_{\text{real}})$. Usually, the tracked head orientation change is applied one-to-one to the virtual camera. With reorientation techniques, rotation gains are defined for each component (pitch/yaw/roll) of the rotation and are applied to the corresponding axis of the camera coordinates. A rotation gain tuple $g_R \in \mathbb{R}^3$ is defined as the quotient of the components of a virtual world rotation R_{virtual} and the real world rotation R_{real}, i. e.,
$$g_R := \left(\frac{pitch_{\text{virtual}}}{pitch_{\text{real}}}, \frac{yaw_{\text{virtual}}}{yaw_{\text{real}}}, \frac{roll_{\text{virtual}}}{roll_{\text{real}}} \right).$$

In this work we investigate body turns and focus on yaw rotations therefore. Moreover, yaws are the most important rotations in redirected walking [JPSW08, PWF08, Raz05]. If a yaw rotation gain $g_{R[yaw]} = \frac{yaw_{\text{virtual}}}{yaw_{\text{real}}}$ is applied to a real world yaw rotation yaw_{real}, the virtual camera is rotated by $yaw_{\text{real}} \cdot g_{R[yaw]}$ instead of yaw_{real}. This means that if $g_{R[yaw]} = 1$ the virtual scene remains stable considering the head's orientation change. In the case $g_{R[yaw]} > 1$ the virtual scene appears to move against the direction of the head turn, whereas a gain $g_{R[yaw]} < 1$ causes the scene to rotate in the direction of the head turn. For instance, if the user rotates her head by a yaw angle of $90°$, a gain $g_{R[yaw]} = 1$ maps this motion one-to-one to a $90°$ rotation of the virtual camera in the VE. The appliance of a gain $g_{R[yaw]} = 0.5$ results in the user having to rotate her head by $180°$ physically in

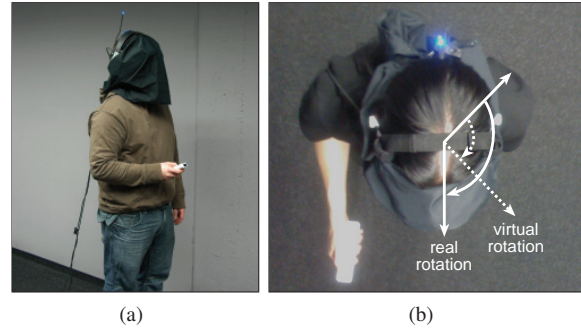(a)   (b)

Figure 1: *Reorientation scenario: (a) user close to a physical wall and (b) user rotating a different angle in the VE compared to the angle in the real world.*

order to achieve a $90°$ virtual rotation (cf. Figure 1); a gain $g_{R[yaw]} = 2$ results in the user having to rotate her head by only $45°$ physically in order to achieve a $90°$ virtual rotation.

4. Experiments

In order to evaluate how much reorientation can be applied during an active body turn, we have conducted two experiments in which we have quantified how much humans can be reoriented without observing inconsistencies between real and virtual body turns. In the first experiment, we examined the subjects' ability to discriminate between two successive body turns in the virtual world. In the second experiment we investigated the subjects' ability to discriminate whether a simulated virtual rotation was slower or faster than the corresponding physical body turn. The results of the experiments will yield thresholds, which show how much humans can be reoriented during body turns.

4.1. Experimental Design

Since the main objective of our experiments is to allow users to walk without restrictions in 3D city environments, the visual stimulus consisted of virtual scenes of a locally developed city model (see Figure 2). Before each trial a random position and a horizontal gaze direction were chosen. The only restriction for the starting scene was that no vertical objects were within $10m$ of the starting position in order to allow an unrestricted view.

Hardware Setup

We performed all experiments in a $10m \times 7m$ darkened laboratory room. The subjects wore an HMD (3DVisor Z800, 800x600@60Hz, $40°$ diagonal field of view) 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

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active optical tracking system (Precision Position Tracking of WorldViz), which provides sub-millimeter 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 orientation tracking we used an InertiaCube 2 (InterSense) with an update rate of 180Hz. The InertiaCube was also fixed on top of the HMD. In the experiments we used an Intel computer with dual-core processors, 4GB of main memory and an *n*Vidia GeForce 8800 GTX for visual display, system control and logging purposes. The virtual scene was rendered stereoscopically using OpenGL and our own software with which the system maintained a frame rate of 60 frames per second. During the experiments the room was completely 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 an input device via which the subjects judged their body turns. In order to focus subjects on the tasks no communication between experimenter 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 orientation by means of auditory feedback in the real world was not possible.

Participants

14 male and 4 female (age 19-31, ∅:24.28) subjects participated in the study. Most subjects were students or members of the departments (computer science, mathematics, psychology, and geoinformatics). All had normal or corrected to normal vision; 9 wore glasses and 1 contact lenses during the experiments. 1 had no experience with 3D games, 5 had some, and 12 had much experience. Two of the authors served as subjects; all other subjects were naïve to the experimental conditions. 10 of the subjects had experience with HMD setups and 7 had participated in user studies involving HMDs before. 2 students obtained class credit for their participation. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks, and debriefing took 2 hours. Subjects were allowed to take breaks at any time; we encouraged subjects to take breaks at least every 10 minutes. All subjects performed both experiments. The order of the experiments was randomized.

Methods

For all experiments we used the method of constant stimuli in a *two-alternative forced-choice* (2AFC) task. In the method of constant stimuli, the applied gains are not related from one trial to the next, but presented randomly and uniformly distributed. The subject chooses between one of two possible responses, e. g., "Was the virtual rotation *faster* or *slower* than the physical rotation?"; responses like "I can't tell." were not allowed. Hence, if subjects cannot detect the

Figure 2: *Example scene from the virtual city model used for experiments E1 and E2. Subjects had to turn towards the red dot.*

signal, they are forced to guess, and will be correct on average in 50% of the trials. The gain at which the subject responds "slower" in half of the trials is taken as the *point of subjective equality* (PSE), at which the subject perceives the physical and the virtual rotation as identical. As the gain decreases or increases from this value the ability of the subject to detect differences between physical and virtual rotations increases, resulting in a psychometric curve for the discrimination performance. Sensory thresholds are the points of intensity at which subjects can barely detect a discrepancy between physical and virtual rotations. In psychophysical experiments, the point at which the curve reaches the middle between the chance level and 100% is usually taken as sensory threshold. Therefore, we define the *detection threshold* (DT) for gains smaller than the PSE to be the value of the gain at which the subject has 75% probability of choosing the "slower" response correctly and the detection threshold for gains greater than the PSE to be the value of the gain at which the subject chooses the "slower" response in only 25% of the trials (since the correct response "faster" was then chosen in 75% of the trials). In this paper we focus on the range of gains over which a subject cannot reliably detect a difference between real and virtual rotations, as well as the gain at which subjects perceive physical and virtual turns as identical. The 25% to 75% range of gains represents an interval of possible manipulations, which can be used for reorientation. The PSE gives indications about how to map a real rotation to the virtual camera such that the virtual rotation appears natural for users. In order to identify potential influences on the results, subjects filled out Kennedy's simulator sickness questionnaire (SSQ) immediately before and after the experiments as well as the Slater-Usoh-Steed (SUS) presence questionnaire.
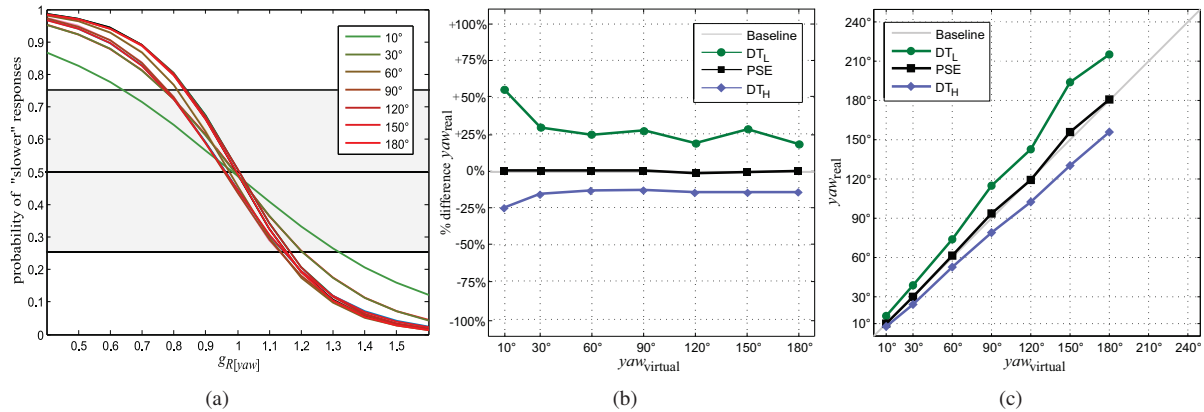
Figure 3: *Pooled results of the discrimination between two successive body turns. (a) The x-axis shows the applied rotation gain $g_{R[yaw]}$, the y-axis shows the probability of estimating the manipulated virtual rotation as "slower" than the rotation with one-to-one mapping. The colored functions show the pooled results for the different virtual angles. (b) The virtual rotation angles $yaw_{virtual}$ are shown on the x-axis and the relative difference of the yaw_{real} angles on the y-axis for the PSE values as well as higher and lower detection thresholds (DT_H and DT_L). (c) The resulting absolute virtual and real rotation angles are shown for the PSE values, DT_H and DT_L.*

4.2. Experiment 1 (E1): Discrimination between Two Successive Body Turns

In this experiment, we examined the subjects' ability to discriminate between two successive body turns in the virtual world.

4.2.1. Material and Methods for E1

At the beginning of each trial the virtual scene was presented on the HMD together with the written instruction – displayed as inset in the virtual view – 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. The end of the first rotation was reached at the time the red dot was in front of the subject. Then the subject had to turn back to the start orientation, which was again indicated by a virtual red dot. The red dots clearly marked the end of the turns and subjects significantly over- or undershot those rotation angles in less than 5% of the trials; we excluded data from these trials from further evaluation. After the body turns the subject had to decide whether the second simulated virtual rotation was slower (down button) or faster (up button) than the first rotation. Before the next trial started, subjects had to turn to a new randomly chosen start orientation. We indicated the reorientation process in the IVE setup by a white screen and two orientation markers (current orientation and target orientation).

In randomized order, we simulated one of the two rotations with a gain $g_{R[yaw]} = 1.0$ between physical and virtual rotation as baseline, 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 5 times in randomized order. We randomly chose the direction of the first rotation between clockwise and counterclockwise for each trial. Each gain was tested with each virtual rotation angle $yaw_{virtual} \in \{10°, 30°, 60°, 90°, 120°, 150°, 180°\}$. In total, each subject performed $9 \times 7 \times 5$ trials. The position in the virtual city model at which the subject had to complete the task was randomized and changed for each trial. Subjects were encouraged to take breaks every 10 minutes. Subjects performed 10 training trials with randomized gains and rotation angles before the actual experiment, which we used to ensure that they correctly understood the task. We further used these trials to ensure that subjects turned at a constant speed with their whole body (non-military like).

4.2.2. Results of E1

Figure 3(a) shows the results of the discrimination experiment. Pooled mean responses over all subjects are plotted for the tested gains and angles. We could not find any impact of the sequence of rotations between the manipulated and one-to-one rotation for the estimation, so we pooled the results from these conditions. Furthermore, we could not find a significant difference between results in the case that the first rotation was directed clockwise or counterclockwise, so we pooled these results too. While for one rotation the gain satisfied $g_{R[yaw]} = 1.0$, the x-axis shows the gain $g_{R[yaw]}$ applied to the other rotation. The y-axis shows the probability that subjects estimated the manipulated virtual rotation as slower than the non-manipulated rotation. The solid lines show the fitted psychometric function for the tested angles of the form $f(x) = \frac{1}{1+e^{a \cdot x + b}}$ with real numbers a and b. From the psychometric functions we determined detection thresholds and

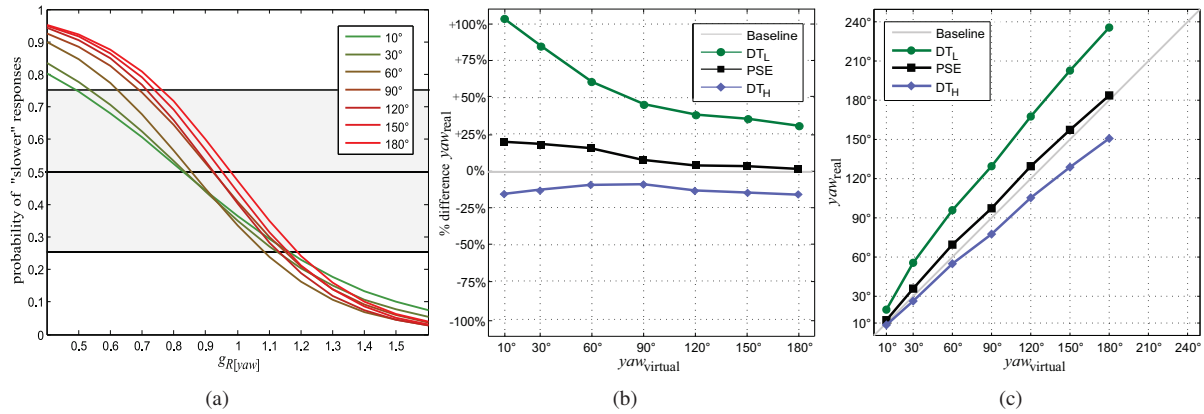|		
(a)	(b)	(c)

Figure 4: *Pooled results of the discrimination between virtual and physical rotations. The x-axis shows the applied rotation gain $g_{R[yaw]}$, the y-axis shows the probability of estimating the virtual rotation as "slower" than the physical rotation. The colored functions show the pooled results for the different tested angles. (b) The virtual rotation angles $yaw_{virtual}$ are shown on the x-axis and the relative difference of the yaw_{real} angles on the y-axis for the PSE values as well as higher and lower detection thresholds (DT_H and DT_L). (c) The resulting absolute virtual and real rotation angles are shown for the PSE values, DT_H and DT_L.*

a bias for the points of subjective equality for the different tested angles, which are listed in Table 1.

$yaw_{virtual}$	PSE	DT_L	DT_H	DT_H-DT_L
$10°$	0.9831	0.6411	1.3247	0.6836
$30°$	0.9903	0.7704	1.2085	0.4381
$60°$	0.9740	0.8120	1.1384	0.3264
$90°$	0.9581	0.7809	1.1366	0.3558
$120°$	1.0040	0.8395	1.1680	0.3286
$150°$	0.9616	0.7737	1.1502	0.3764
$180°$	0.9952	0.8349	1.1558	0.3209

Table 1: *PSE values, lower and higher detection thresholds (DT_L and DT_H) and the length of the manipulation interval for the virtual rotation angles $yaw_{virtual}$ in experiment E1.*

Figure 3(b) shows the relative difference of the yaw_{real} angles for the PSE values as well as the higher and lower detection thresholds compared to the $yaw_{virtual}$ angles. In Figure 3(c) the absolute real rotation angles are plotted against the virtual angles. For all tested virtual rotation angles we found no significant bias for the PSE. The results show that the subjects were best at discriminating rotations at a virtual rotation angle of $180°$. At this angle subjects cannot discriminate a virtual $180°$ rotation from physical rotations between $155.74°$ and $215.60°$, i.e., physical rotations can deviate by 13.48% downwards or 19.78% upwards. The results further show that subjects had serious problems discriminating rotations at a virtual rotation angle of $10°$. In this condition, subjects were unable to discriminate physical rotations between 24.51% downwards and 55.98% upwards from $yaw_{real} = 10°$. The detection thresholds for virtual ro-

tation angles between $30°$ and $180°$ showed no significant differences. In summary, the results show that subjects have serious problems discriminating two successive rotations, in particular for small virtual rotation angles, in which case rotation gains can be varied significantly from one body turn to the next without users perceiving the difference.

4.3. Experiment 2 (E2): Discrimination between Virtual and Physical Body Turns

In this experiment we investigated the subjects' ability to discriminate whether a simulated virtual rotation was slower or faster than the corresponding physical body turn. Therefore, we instructed the subjects to rotate on a physical spot and we mapped this body turn to a corresponding virtual camera rotation to which different gains were applied.

4.3.1. Material and Methods for E2

The experimental setup was almost identical to that of experiment E1. At the beginning of each trial the virtual scene was presented on the HMD together with a 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. The red dot clearly marked the end of the turn and subjects significantly over- or undershot that rotation angle in less than 5% of the trials; we excluded data from these trials from further evaluation. Afterwards the subjects had to decide whether the simulated virtual rotation was slower (down button) or faster (up button) than the physical body turn. Before the next trial started, subjects had to turn to a new start orientation. We indicated the reorientation

process in the IVE setup by a white screen and two orientation markers (current orientation and target orientation).

In randomized order we tested virtual rotations $yaw_{\text{virtual}} \in \{10°, 30°, 60°, 90°, 120°, 150°, 180°\}$ in clockwise and counterclockwise direction. We varied the gain $g_{R[yaw]}$ between the physical and virtual rotation randomly in the range between 0.5 and 1.5 in steps of 0.1. We tested each gain 5 times in randomized order. In total, each subject performed $11 \times 7 \times 5$ trials. The position in the virtual city model at which the subject had to complete the task was randomized and changed for each trial. Subjects were encouraged to take breaks every 10 minutes. Subjects performed 10 training trials with randomized gains and rotation angles prior to the experiment, which we used to ensure that they correctly understood the task and turned at a constant speed with their whole body.

4.3.2. Results of E2

Figure 4(a) shows the pooled mean results over all subjects for the tested gains and angles. The *x*-axis shows the applied rotation gain $g_{R[yaw]}$, the *y*-axis shows the probability for estimating a virtual rotation "slower" than the corresponding physical rotation. The colored solid lines show the fitted psychometric functions corresponding to the virtual rotation angles of the same form as used in Section 4.2.2. We found no difference between clockwise and counterclockwise rotations and pooled the two conditions. From the psychometric functions we determined detection thresholds and a bias for the point of subjective equality, which are listed in Table 2.

yaw_{virtual}	PSE	DT_L	DT_H	DT_H-DT_L
10°	0.8309	0.4952	1.1680	0.6728
30°	0.8349	0.5384	1.1312	0.5928
60°	0.8558	0.6235	1.0874	0.4639
90°	0.9229	0.6938	1.1542	0.4605
120°	0.9248	0.7168	1.1341	0.4173
150°	0.9521	0.7407	1.1634	0.4227
180°	0.9796	0.7642	1.1928	0.4286

Table 2: *PSE values, lower and higher detection thresholds (DT_L and DT_H) and the length of the manipulation interval for the virtual rotation angles $yaw_{virtual}$ in experiment E2.*

In Figures 4(b) and 4(c) the virtual rotation angles yaw_{virtual} are plotted against the relative and absolute real rotation angles yaw_{real} for the PSE values as well as higher and lower detection thresholds. The results show that for a virtual rotation angle of $yaw_{\text{virtual}} = 180°$ subjects cannot discriminate between physical rotations that deviate by 16.16% downwards or 30.86% upwards, i.e., physical rotations between 150.91° and 235.54° cannot be discriminated from a 180° rotation. The results further show that subjects had serious problems discriminating real and virtual rotations at a virtual angle of 10°. In this condition, subjects cannot discriminate rotations between 14.38% downwards and

101.94% upwards from $yaw_{\text{real}} = 10°$. For virtual 180° rotations we found no significant bias for the PSE, whereas virtual 10° rotations showed a PSE of $g_{R[yaw]} = 0.8309$, which corresponds to a 20.35% underestimation of the physical rotation speed. In summary, the experiment shows that subjects had serious problems discriminating physical and virtual rotations, in particular for small virtual rotation angles. Furthermore, we found that subjects tended towards underestimation of the physical rotation speed for smaller virtual rotation angles, i.e., subjects estimated virtual and physical rotation angles as equal if the real rotation angles were up to 20.35% greater (for $yaw_{\text{virtual}} = 10°$).

5. Discussion

Our results show that users are better at discriminating rotations in case the virtual turning angle is rather large. For virtual 180° rotations users can be manipulated to turn physically about 30.86% more or 16.16% less than the corresponding rotation in the virtual world without perceiving a difference. Furthermore, at this virtual rotation angle, users can detect different applied rotation gains in two successive rotations, which deviate by more than 15.58% upwards or 16.51% downwards. The results show that the users' ability to detect manipulations decreases when the virtual rotation angle decreases. We found that users can be manipulated to turn physically about 101.94% more or 14.38% less than in the virtual world for a virtual rotation angle of 10°. We further found that rotation gains applied to two successive turns can deviate by up to 32.47% upwards or 35.89% downwards for this virtual rotation angle. Consequently, manipulation of users via rotation gains is especially useful for small virtual rotation angles, since applied gains can vary more from one rotation to the next and higher gains can be applied.

The results of experiment E2 for virtual rotation angles of 90° are similar to those found by Steinicke et al. [SBJ*09], where the PSE was at $g_{R[yaw]} = 0.96$ and detection thresholds indicated that subjects could be turned physically about 49% more or 20% less than in the virtual world. Steinicke et al. [SBJ*09] also found a bias towards underestimation of the physical rotation speed in their experiments, in which they only tested virtual 90° rotations.

We have performed questionnaires in order to identify potential influences on the results. The subjects estimated the difficulty of the tasks with 1.28 on average on a 5-point Likert-scale (0 corresponds to very easy, 4 corresponds to very difficult). Further questionnaires based on comparable Likert-scales show that the subjects only had marginal orientational cues due to ambient noise (0.61), light sources (0.11) and cables (0.83) in the real world. The subjects' mean estimation of their level of feeling present in the VE according to the Slater-Usoh-Steed (SUS) presence questionnaire averaged as 3.40. Kennedy's simulator sickness questionnaire (SSQ) showed an averaged pre-experiment score of 7.48 and a post-score of 30.96.

6. Conclusion and Future Work

We analyzed the users' ability to detect reorientation during body turns in two different experiments. We tested the intensity of these manipulations, i. e., rotation gains defining the discrepancy between real and virtual motions, in a practically useful range for their perceptibility and set these results in correlation to the angles users turn in the virtual world. In contrast to presumptions from previous studies, we have found that the virtual rotation angle has a rather great impact on the perceptibility of manipulations and hence on the implementation of reorientation techniques. The PSE between real and virtual motions, and in particular detection thresholds vary significantly for different rotation angles.

Our results show that the rotation angle affects the PSE, for which virtual rotations appear most natural to users. We did not observe a significant bias for virtual $180°$ rotations, but the bias increased for smaller rotation angles up to $g_{R[yaw]} = 0.8309$ for an angle of $10°$. This result agrees with previous findings [JPSW08, SBJ*09] that users appear to be more sensitive to scene motion if the scene moves against the head rotation direction than if the scene moves with head rotation. In [JS09] Jerald and Steinicke discuss potential reasons for the phenomenon for virtual $90°$ turns. With respect to the observed fact that subjects tend to underestimate virtual translation distances, it is an interesting observation that the results of our experiments suggest that subjects tend to overestimate virtual rotations. However, further analyses are needed to clarify if the bias vanishes for angles greater than $180°$ or is shifted towards overestimation of rotation speed.

In the future we will consider further aspects which might have an impact on perceptibility of reorientation techniques. In particular, adaptation may have a significant impact on the users' ability to detect manipulations. Users may adapt to applied rotation gains over time or space, i. e., depending on the rotation duration or angle. Furthermore, the visual stimulus, i. e., the structure of the virtual scene, influencing saccadic eye motions and reflexes, may have an impact on perceptibility of manipulations.

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