Impact of Gender on Discrimination between Real and Virtual Stimuli

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Abstract

Immersive virtual environments allow users to control their virtual viewpoint by moving the tracked head or by walking through the real world. Usually, movements in the real world are mapped one-to-one to virtual camera motions. With redirection techniques, gains are applied to user movements when the virtual camera is manipulated. Since male and female persons use different strategies for spatial cognition and navigation, it sounds reasonable that these gender differences also occur for redirection techniques. In this paper we examine the impact of gender on tasks where male and female subjects have to discriminate between virtual and real stimuli. 7 male and 6 female subjects have been tested in three different experiments: discrimination between virtual and physical rotation, discrimination between virtual and physical translation and discrimination of walking direction.

Keywords: Virtual reality, perception, redirected walking, gender differences.

Index Terms: 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 in 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. IVEs are characterized, for instance, by head-mounted displays (HMDs) and a tracking system for measuring position and orientation data.

Many domains are inherently three-dimensional and advanced visual simulations often provide a good sense of locomotion. However, exclusive visual stimulation does not provide vestibular-proprioceptive motion cues as during real-world walking. *Real walking* through IVEs is often not possible [17]. Indeed, an obvious approach is to transfer the user's tracked head movements to changes of the 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. Hence, the size of the tracked laboratory space limits the size of the explorable virtual world so that a straightforward implementation of omnidirectional and unlimited walking is not possible.

It is known from perceptive psychology that vision often dominates proprioceptive and vestibular sensation when they disagree [1]. Furthermore, users tend to unwittingly compensate for small inconsistencies between real world movements and visually perceived motions during walking, so that it gets possible to guide them along paths in the real world, which differ from the path perceived in the virtual world. This *redirected walking* [14] enables users to explore a virtual world that is considerably larger than the tracked working space. Paths that users walk in the physical world can be scaled and bended, and real-world rotations of users can be increased or decreased when the motions are applied to the virtual camera [16].

It is generally accepted that gender differences in spatial cognition and navigation strategies exist [9, 13]. Most reports document that males outperform females in spatial tasks. Some authors argue that this may be a result of evolution, experience or training due to different interests, e. g., computer games [4]. Other authors argue that males and females use different cues for spatial orientation [15]. Until now, it has not been considered if gender has any impact on the ability to discriminate between real and virtual motions.

In this paper we analyze gender differences in sensitivity to redirected walking techniques. We performed a series of experiments in which we have quantified how much male and female subjects can be redirected without observing inconsistencies between real and virtual motions. Therefore, we have performed three psychophysical experiments in which subjects had to discriminate between real and virtual motions, in particular rotations, translations and walking directions.

The remainder of this paper is structured as follows. Section 2 summarizes previous work related to locomotion and perception in virtual reality (VR) environments as well as gender differences in spatial cognition. In Section 3 we explain the redirected walking gains that we have considered in our experiments. The experiments 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 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 from other parts of the mind or body help us to perceive the world as stable [18]. 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 spatially unstable.

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Experiments demonstrate that users tolerate a certain amount of inconsistency between visual and proprioceptive sensation [2, 8, 10, 12, 14]. With redirected walking [14] users are manipulated via gains that are applied to tracked user motions, 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 larger virtual distance than the distance walked in the physical space. Interrante et al. suggest to apply scalings exclusively to the main walking direction in order to prevent unintended lateral shifts [7]. Most reorientation techniques are based on rotating the virtual world around the center of stationary users in order to reorient them in the real world [10, 12, 14]. Hence, in case an obstacle blocks a user's path in the real world, this approach allows to reorient users so that later on they can continue to walk in the desired virtual direction. Alternatively, reorientation can be applied while users walk [14]. For instance, if users walk straight ahead for a long distance in the virtual world, small rotations of the camera redirect them to walk imperceptibly a circular path in the real world. In such cases the visual sensation is consistent with motion in the IVE, but proprioceptive sensation reflects real-world motion. However, if the induced manipulations are small enough, users get the impression of being able to walk in the virtual world in any direction without restrictions.

Preliminary studies [12, 14] have shown that redirected walking works as long as users are not focused on detecting manipulations. In these experiments users had to remark afterwards, if they noticed a manipulation or not. Other work has focused on identifying thresholds for detecting scene motion during head rotation [8, 18].

3 Locomotion Gains

In this Section we describe how gains are applied to tracked motions when these are mapped to the virtual camera.

3.1 Translation gains

When the tracking system detects a change of the user's real world head 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 to the virtual camera with respect to the registration between virtual scene and tracking coordinate system. In case of a one-to-one mapping, the virtual camera is translated by $|T_{\text{real}}|$ units in the corresponding direction in the virtual world coordinate system. A translation gain $g_T \in \mathbb{R}^3$ is defined as 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 is particularly useful if the user wants to explore IVEs whose size differs significantly from the size of the tracked space. For instance, if a user wants to explore molecular structures, movements in the real world must be scaled down when they are mapped to virtual movements, e. g., $g_T \approx 0$. In contrast, exploration of a virtual football field in a typical walking setup requires a translation gain $g_T \approx 10$. Generic gains for translational movements can be expressed by $g_{T[s]}, g_{T[u]}, g_{T[w]}$, where the components are applied to movements in strafe direction s, up direction u and walking direction w, which compose the translation. In our experiments we have focused on sensitivity to translation gains $g_{T[w]}$.

3.2 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 3.1, rotation gains are defined for each component (pitch/yaw/roll) of the rotation. 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. For instance, if a user rotates the head by 90°, a gain $g_R = 1$ maps this motion one-to-one to a 90° rotation of the virtual camera. 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 45° physically in order to achieve a 90° virtual rotation.

Rotation gains can be expressed by $g_{R[s]}, g_{R[u]}, g_{R[w]}$, where the gain $g_{R[s]}$ specified for pitch corresponds to s, the gain $g_{R[u]}$ specified for yaw corresponds to u, and $g_{R[w]}$ specified for roll corresponds to w. In our experiments we have focused on rotation gains $g_{R[u]}$ for yaw rotation.

3.3 Curvature gains

Instead of multiplying gains with translations or rotations, offsets can be added to real-world movements. For instance, rotational offsets can be applied to the camera with respect to traveled distances while a user walks straight ahead in the virtual world. If the injected manipulations are reasonably small, the user will unknowingly compensate for these virtual camera rotations resulting in walking a curve in the real world. The curvature gain g_C denotes the resulting bend of a real path. When a user moves straight ahead in the virtual world, 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 $r = 1 \Rightarrow g_C = 1$.

In our experiments we have focused on curvature gains $g_{C[w]}$, which enforce users to walk an circular arc.

4 Experiments

In this section we present three experiments in which we have quantified how much female and male subjects 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

The visual stimulus consisted of virtual scenes of the city of Münster in Germany (see Figure 2). Before each trial a random place and initial gaze direction were chosen. The only restriction for scenes was that no vertical objects were within 10m of the starting position in order to prevent collisions in the VE.

Hardware Setup

We performed all experiments in a 10 × 10m laboratory room. The subjects wore an HMD (eMagin Z800 3DVisor, 800x600@60 Hz, 40° diagonal field of view (FoV)) for stimulus presentation. On top of the HMD an infrared LED was fixed. We tracked the position of this LED in the room with an active optical tracking system (WorldViz Precise Position Tracking), which provides sub-millimeter precision and sub-centimeter accuracy. The update rate was 60 Hz providing real-time positional data of the active marker. For three degrees of freedom (DoF) orientation tracking we used an InterSense InertiaCube 2 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 with dual-core processor, 4 GB of main memory and an *n*Vidia GeForce 8800 GTX for rendering and system control. We connected the HMD and InertiaCube with a 10m cable to the rendering computer.

The virtual scene was rendered using OpenGL and our own software with which the system maintained a frame rate of $50-60$ frames per second. During the experiment the room was entirely darkened in order to reduce the user's perception of the real world. Furthermore, ambient city noise was used as acoustic feedback during the experiment such that orientation by means of auditory cues from the real world was not possible. Prior to each experiment the subjects received instructions on slides presented on the HMD. A Nintendo WII remote controller served as input device. In order to focus subjects on the task no communication between experimenter and subject was performed during the experiment. Task instructions were displayed as insets in the visual scene and subjects responded via the WII device.

Participants

7 male (age $21-24$, $\varnothing : 22.7$) and 6 female (age $19-50$, $\varnothing : 27.3$) subjects participated in the experiments. Subjects were students or professionals with expertise in computer science, mathematics or psychology. All had normal or corrected to normal vision; 4 wore glasses and 3 contact lenses during the experiments. 3 of the males had some gaming experience and 4 had much gaming experience; 2 females had no, 3 some and 1 much gaming experience. All subjects were naïve to the experimental conditions. None of the subjects had experience with walking in VR environments using an HMD setup. Subjects were allowed to take breaks at any time. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks, and debriefing took 3 hours.

Experiments

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 choses between one of two possible responses, e. g. "Was the virtual movement *smaller* or *greater* than the physical movement?"; responds like "I can't tell." were not allowed. Hence, when subjects cannot detect the signal, they must guess, and will be correct on average in 50% of the trials. The gain at which a subject responds "greater" in half of the trials is taken as the *point of subjective equality* (PSE), at which the subject perceives the physical and 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. We define the *detection threshold* (DT) for gains smaller than the PSE to be the gain at which the subject has 75% probability of correctly choosing the "smaller" response and the detection threshold for gains greater than the PSE to be the gain at which the subject chooses the "smaller" response in only 25% of the trials (since the correct response "greater" was then chosen in 75% of the trails).

Figure 2: Example scene from the virtual city model as used for experiment E2. No obstacles were within a 10m distance from the user.

The range of gains will give us an interval of possible manipulations which can be used for redirected walking. The PSEs indicate how to map user movements to the virtual camera such that virtual motions appear natural to users.

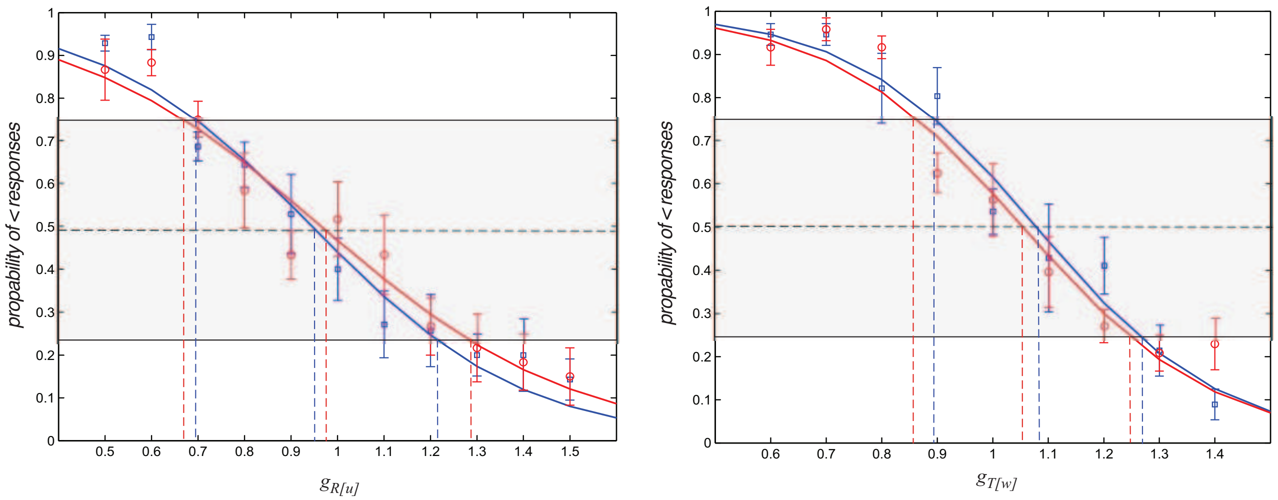
4.2 Experiment 1 (E1): Discrimination between virtual and physical rotation

In this experiment we investigated the subjects' ability to discriminate whether a physical rotation was smaller or greater than the simulated virtual rotation (see Section 3.2). Therefore, we instructed the subjects to rotate on the spot and we mapped the physical rotation to a corresponding virtual rotation to which different gains $g_{R[u]}$ were applied.

4.2.1 Material and Methods for E1

At the beginning of each trial the virtual scene was presented on the HMD together with written instruction to physically turn left or right until a red dot drawn at eye height was directly in front of the subject's gaze direction. The subject indicated the end of the turn with a button press on the WII controller. Afterwards, the subject had to decide whether the simulated virtual rotation was greater (up button) or smaller (down button) than the physical rotation in the described 2AFC task. Before the next trial started, the subject 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 reorientation in order to prevent adaptation of the subject to a certain pose and orientation.

The virtual rotation was always 90° either clockwise or counterclockwise. 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.



(a) (b)

Figure 1: Pooled results of the discrimination between (a) virtual and physical rotation, and (b) virtual and physical translation. In (a) the x-axis shows the applied rotation gain $g_{R[u]}$, the y-axis shows the probability of estimating a virtual rotation smaller than the physical rotation. In (b) the x-axis shows the applied translation gain $g_{T[w]}$, the y-axis shows the probability of estimating a virtual translational movement smaller than the physical motion.

4.2.2 Results of E1

Figure 1(a) shows the mean detection rates together with the standard error over all male subjects (blue symbols) and female subjects (red symbols) for the tested gains. The x-axis shows the applied rotation gain $g_{R[u]}$, the y-axis shows the probability for estimating a virtual rotation smaller than the rotation in the real world. The solid lines show the fitted sigmoid functions 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 clockwise or counterclockwise rotations and pooled the two conditions.

Using the sigmoid function we determined a bias for the point of subjective equality resulting in a PSE of 0.9447 for men and 0.9642 for women. Detection thresholds for men were at gains of 0.69 for smaller responses and at 1.19 for greater responses, respectively for women at gains of 0.66 for smaller and at 1.26 for greater responses. The results show that subjects had serious problems to discriminate between a 90° virtual rotation and real rotations ranging from 76° to 130° for men and from 71° to 136° for women.

4.2.3 Discussion of E1

According to previous results [8] we assumed an asymmetric psychometric function, which could be reproduced in our experiment (see Figure 1(a)). Men can be turned physically about 44% more or 16% less than the perceived virtual rotation. Women can be turned physically about 51% more or 21% less than the virtual rotation. The asymmetry of the detection thresholds and slightly biased PSEs imply that a gain $g_{R[u]} < 1$ downscaling a physical rotation is less noticeable for subjects. In this case the scene seems to move slightly with the head rotation [8].

Subjects estimated a physical rotation identical to a virtual rotation that was scaled with the PSE gain $g_{R[u]} = 0.9447$ for men and PSE $g_{R[u]} = 0.9642$ for women. Such gains correspond to underestimation of rotations by approximately 5% for men and 3% for women. A significant difference for the thresholds and the PSEs between male and female subjects could not be verified.

In summary, the experiment shows that both male and female subjects had serious problems discriminating rotations. Consequently, reorientation techniques based on rotation gains are a good choice in order to redirect subjects, since they allow strong manipulations for all users.

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

In this experiment we analyzed the subjects' ability to discriminate between virtual and physical translational movements (see Section 3.1). The virtual movement was a forward movement mapped to physical walking.

4.3.1 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. When the subjects traveled 5m in the virtual scene, the dot turned red to indicate the end of the trial (see Figure 2). The dot was constant in size and positioned in the subject's eye height above the ground. The physical distance subjects had to walk varied between 3m and 7m, i. e., translation gain $g_{T[w]}$ was between 0.6 and 1.4 in steps of 0.1. We presented the gains each 8 times in randomized order. The task was to judge whether the physical walking distance was larger or smaller than the virtual travel distance. After each trial the subject had to walk back to the start 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 start position.

4.3.2 Results of E2

In Figure 1(b) we plotted the mean probability for a subject's estimation that the virtual walking distance was shorter than the physical travel distance over all male subjects (blue symbols) and female subjects (red symbols) against the tested gains. The error bars show the standard errors. A translation gain $g_{T[w]} < 1$ resulted in a larger physical walking distance compared to the virtual distance,

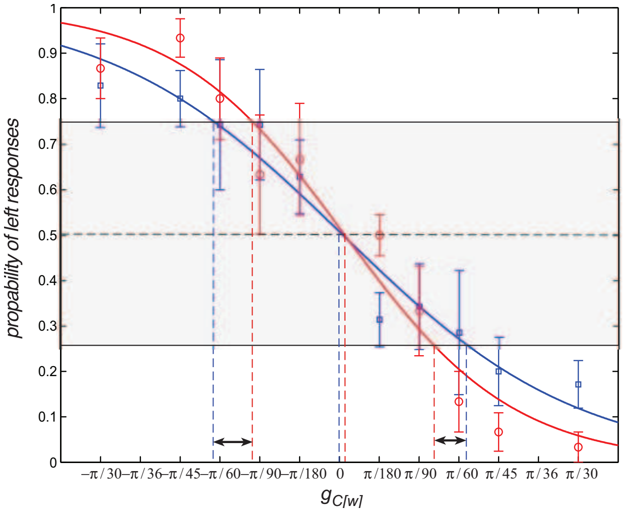


Figure 3: Pooled results of the walk direction discrimination experiment. The x-axis shows the applied curvature gain, which bends the walked path either to the left ($g_{C[w]} < 0$) or the right ($g_{C[w]} > 0$), the y-axis shows the probability of estimating a path bended to the left.

a gain $g_{T[w]} > 1$ resulted in a shorter physical distance. We fitted the data with the same sigmoidal function as in experiment E1. The PSE for the pooled data of the male subjects was 1.0776, and 1.0535 for the female subjects. Hence, the male subjects estimated that they walked the 5m virtual distance after 4.64m in the real world, the female subjects after 4.75m. DTs for estimation of translational movements are given at gains of 0.9 for smaller responses and 1.26 for greater responses for men, and at gains of 0.86 for smaller and 1.24 for greater responses for women. The DTs mean that men could not discriminate reliably between physical distances of 3.97m and 5.56m while they walked 5m in the virtual world. Women could not discriminate physical distances between 4.03m and 5.81m while walking 5m in the virtual world.

4.3.3 Discussion of E2

According to underestimation of egocentric distances in virtual worlds [5, 6, 11], we assumed an asymmetric psychometric function, which could be reproduced in our experiment (see Figure 1(b)). The results show that men can be manipulated to walk physically about 11.2% more or 20.6% less than the perceived virtual distance, women can walk physically about 16.2% more or 19.4% less than in the virtual world. In this experiment we found PSEs at $g_{T[w]} = 1.0776$ for men and $g_{T[w]} = 1.0535$ for women. Hence, men need to walk 4.64m in the real world in order for a walked distance of 5m in the virtual world to appear natural, females have to walk 4.75m physically. This corresponds to 7% overestimation of physically walked distances for males and 5% for females respectively. The differences in PSEs and detection thresholds for male and female subjects were not significant.

In summary, the results indicate that men and women can discriminate between virtual and real translational movements quite accurately when walking in a familiar environment such as a realistic 3D city model. Subjects knew the VE from the real world and might have exploited distance cues such as the height of trees, buildings etc. As stated in [7] such cues support subjects when estimating distances.

4.4 Experiment 3 (E3): Discrimination of direction of walk

In this experiment we analyzed the subjects' sensitivity to curvature gains, which enforce the user to walk a curved path in the real world in order to walk a straight path in the VE (see Section 3.3). In previous experiments we found that subjects had difficulty estimating the direction of path bending in similar discrimination tests particularly during the first steps [16]. For instance, after two gaits, they had left the sidewalk and had to reorient themselves to the target. Consequently, they tended to walk a triangular rather than a circular path. Therefore, we introduced a 2m travel distance without scene manipulation before curvature gains $g_{C[w]}$ were applied.

4.4.1 Material and Methods for E3

To support the subjects' task to walk straight in the virtual world, we introduced a 1m wide sidewalk. We added a green dot at the subject's eye height in the scene, which turned red when the subjects had walked 5m. While the subject walked along the sidewalk, we rotated the scene to either side with a velocity linked to the subject's movement velocity. The scene rotated by $5, 10, 15, 20$ or 30 degrees after 5m walking distance. This corresponds to curvature radii of approximately 57.3, 28.65, 14.32, 19.10 and 9.55m. The curvature gains were $g_{C[w]} = \{\pm\frac{\pi}{30}, \pm\frac{\pi}{45}, \pm\frac{\pi}{60}, \pm\frac{\pi}{90}, \pm\frac{\pi}{180}\}$. The rotation started after subjects walked the 2m start-up phase. After subjects walked further 5m in the virtual world, the screen turned white and the task instruction appeared. The subject's task was to decide whether the physical path was curved to the left or to the right by pressing the corresponding "left" or "right" button on the WII controller. To guide the subject back to the starting position we used the two markers (as described above) on an otherwise white screen again.

4.4.2 Results of E3

In Figure 3 we plotted the mean probability of estimating that the physical path was curved to the left against the curvature gains $g_{C[w]}$ over all male subjects (blue symbols) and female subjects (red symbols). The variance is the standard error. The detection thresholds are given by the gains at which subjects correctly detect the bending of the path 75% of the time. We found no statistical significant difference whether we simulated a curvature to the left or right. For male subjects the DT is given by $g_{C[w]} = \pm\frac{\pi}{54.66}$, which corresponds to a circular arc with radius 17.4m. The DT for female subjects is $g_{C[w]} = \pm\frac{\pi}{78.23}$, i. e., a circular arc with radius 24.9m. Until these DTs subjects cannot reliably estimate if they walk straight or a curved path.

4.4.3 Discussion of E3

The results show that men can be reoriented by 16° to the left or to the right after walking a 5m distance, which corresponds to walking along a circular arc with radius of approximately 17.4m. Women can be reoriented by 11° after 5m walking distance, which corresponds to a radius of approximately 24.9m. The results for male and female subjects show no statistical significant bias for the PSE. Furthermore, a statistical significant difference for the detection thresholds between male and female subjects could not be verified due to strong individual differences and the low number of subjects.

5 Conclusion and Future Work

In this paper, we analyzed the ability of male and female subjects to recognize redirected walking manipulations in three different experiments. The results show that male subjects can be turned physically about 44% more or 16% less than the perceived virtual rotation without noticing the difference. Female subjects can be turned physically about 51% more or 21% less than the virtual rotation. We determined a bias for the point of subjective equality resulting in a PSE of 0.9447 for men and 0.9642 for women. Our results agree with previous findings [8, 16] that users are more sensitive to scene motion if the scene moves against head rotation than if the scene moves with head rotation. Considering also results of other researchers [3, 8, 16], it seems that male as well as female subjects tend to underestimate virtual rotations.

For male subjects, walked distances in the real world can be down-scaled by 20.6% and up-scaled by 11.2%, when they are mapped to virtual motions. For female subjects, physical walking distances can be down-scaled by 19.4% and up-scaled by 16.2%. The PSE for the pooled data of the male subjects is 1.0776, and 1.0535 for the female subjects. These results agree with previous findings that users tend to underestimate virtual distances [5, 6, 11]. Male subjects estimate that they have walked a distance of 5m after walking only 4.64m, whereas female subjects walk 4.75m.

When applying curvature gains users can be redirected such that they unknowingly walk a circular arc when the radius is greater or equal to 17.4m for male and 24.9m for female subjects. In this experiment the detection thresholds vary most for male and female subjects, which motivates that gender might have a significant influence on sensitivity to curvature gains. However, due to the low number of subjects this difference could not be verified with a test of significance.

We have performed further questionnaires in order to determine the subjects' fear of colliding with physical obstacles. The subjects revealed their level of fear on a four point Likert-scale (0 corresponds to no fear, 4 corresponds to a high level of fear). On average the evaluation approximates 1.33 which shows that subjects felt quite 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 subjects only had marginal positional and orientational indications due to environmental audio (0.6), visible (0.13) or haptic (1.33) cues. We measured simulator sickness by means of Kennedy's simulator sickness questionnaire (SSQ). The Pre-SSQ score averages to 13.35 for male and 8.1 for female subjects, and the Post-SSQ score to 25.64 for male and 26.18 for female subjects. In [16] we conducted a follow-up test on another day for subjects with high Post-SSQ scores in order to examine 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. Hence, probably cybersickness was caused by the long period of time subjects had to wear the HMD.

In the future we will test for a significant difference in sensitivity to curvature gains with a larger number of male and female subjects and we will consider other redirection techniques, which have not been analyzed in the scope of this paper. Moreover, further conditions have to be taken into account and tested for their impact on redirected walking, for example, gaming experience, distances of scene objects, level of detail, contrast, etc.

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