Velocity-Dependent Dynamic Curvature Gain for Redirected Walking

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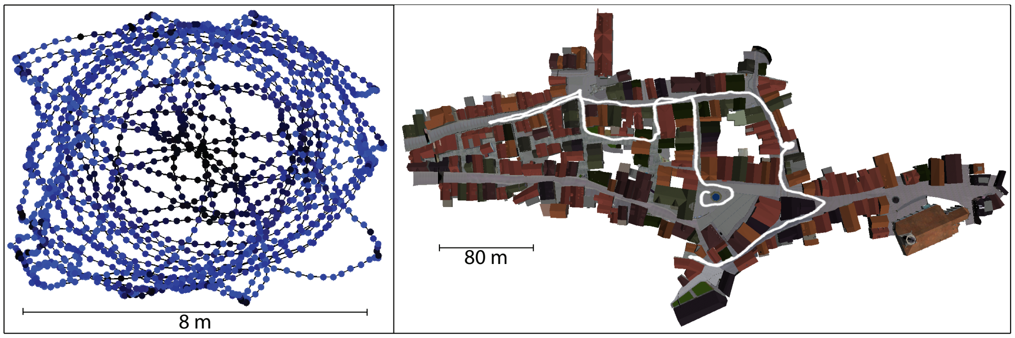

Figure 1: Illustration of walked paths of the real world (left) and in Virtual Tübingen (right).

Abstract

The aim of Redirected Walking (RDW) is to redirect a person along their path of travel in a Virtual Environment (VE) in order to increase the virtual space that can be explored in a given tracked area. Among other techniques, the user is redirected on a curved real-world path while visually walking straight in the VE (*curvature gain*). In this paper, we describe two experiments we conducted to test and extend RDW techniques. In Experiment 1, we measured the effect of walking speed on the detection threshold for curvature of the walking path. In a head-mounted display (HMD) VE, we found a decreased sensitivity for curvature for the slowest walking speed. When participants walked at 0.75 m/s, their detection threshold was approximately 0.1m^{-1} (radius of approximately 10m). In contrast, for faster walking speeds ($\geq$1.0m/s), we found a significantly lower detection threshold of approximately 0.036m^{-1} (radius of approximately 27m).

In Experiment 2, we implemented many well known redirection techniques into one dynamic RDW application. We integrated a large virtual city model and investigated RDW for free exploration. Further, we implemented a dynamic RDW controller which made use of the results from Experiment 1 by dynamically adjusting the applied curvature gain depending on the actual walking velocity of the user. In addition, we investigated the possible role of avatars to slow the users down or make them rotate their heads while exploring. Both the dynamic curvature gain controller and the avatar controller were evaluated in Experiment 2. We measured the average distance that was walked before reaching the boundaries of the tracked area. The mean walked distance was significantly larger in the condition where the dynamic gain controller was applied. This distance increased from approximately 15m for static gains to approximately 22m for dynamic gains. This did not come at the cost of an increase in simulator sickness. Applying the avatar controller did reveal an effect on walking distance or simulator sickness.

Index Terms: Computer Graphics [I.3.7]: Three-Dimensional Graphics and Realism—Virtual Reality

1 Introduction & Motivation

When we walk through the world, various sensory systems provide the brain with information concerning our changing position. On the one hand, the vestibular and proprioceptive systems produce signals that arise from within our body. At the same time, the visual system provides the brain with information about how our position is changing with respect to our surroundings. Normally, these different sensory signals are congruent and produce the same estimate of self-motion. Sometimes, however, conflicts arise and the brain has to either combine the conflicting signals or choose which signal to use. In such a conflict situation, the visual modality often dominates (summarized in [21]). This fact is exploited in *Redirected Walking*, in order to increase the size of Virtual Environments which can be explored on foot. In addition, contemporary display hardware provides great means of presenting arbitrarily generated images to the user whereas other senses are relatively hard to manipulate.

The aim of *Redirected Walking* (RDW, [16]) is to allow users to walk in virtual worlds which are of greater dimensions than the real-world space they walk in. The idea behind RDW is to manipulate the camera movement through the VE compared to the user's tracked real movements, hereby decoupling the 1:1 mapping of the user's position and orientation. This leads to a redirection of the actual walked path from the corresponding, intended virtual walking trajectory. Thus, virtual worlds of greater extents than the operative area of the tracking system can be explored by walking. Among other means of manipulation, there is the possibility to introduce

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a small rotation to the virtual camera with respect to the forward motion of the user. By trying to correct this deviation, the user walks on a curved path in the real world while walking straight in the VE (see figure 2). As long as the induced curvature is small

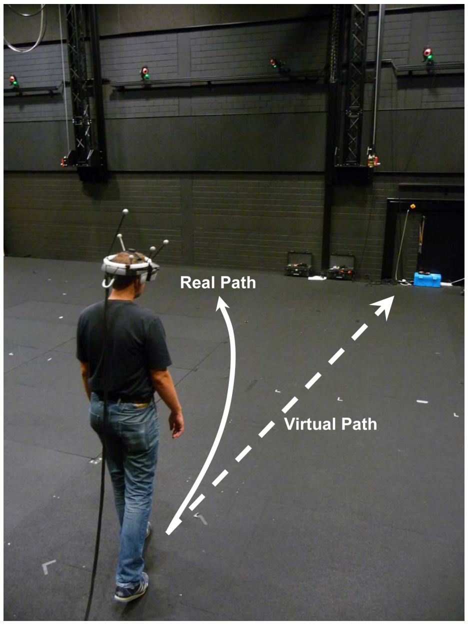

Figure 2: The principle of Redirected Walking

enough, this manipulation is not noticed by the users. Related work [4, 29] has successfully used RDW to allow users to walk arbitrarily far through virtual worlds of greater dimensions than the available tracking area. Yet whereas the primary methods of RDW are based on manipulating the mapping between real and virtual world, there recently have been approaches to manipulate the user's walking behaviour by changing the virtual world (e.g., [25] changed the location of doors in a virtual room exploiting the phenomena of change blindness).

In this paper, we present two separate experiments which investigated RDW. First, in a psychophysical experiment, we investigated the sensitivity of humans to walking on a curved path using an HMD virtual world. Then, we implemented many of the commonly used techniques for redirection in virtual worlds, extending these algorithms for free exploration in a large virtual city.

In our second experiment we investigated the usefulness of the results from our first experiment, and we also further extended the idea of using distractors [15] to additionally redirect the user by using avatars to manipulate their walking behaviour. As it was shown that people feel uncomfortable when avatars approach too close [10, 1], we aim to use avatars to *repel* users when approaching physical obstacles.

2 Related Work

In order to understand the motivation for our two experiments, we must discuss both the understanding of human sensitivity to walking straight, and the current state-of-the-art for redirected walking algorithms. Therefore, first we introduce existing RDW techniques. Then, we introduce reorientation techniques (ROTs), used when RDW algorithms are not sufficient, and specifically introduce avatars as potentially useful distractors while being redirected. Finally, we introduce related research on curvature sensitivity and the role that velocity may have for curvature sensitivity while walking.

2.1 Redirected Walking setups

Redirected Walking has first been described by [16]. In this experiment, a fire drill was modelled which led the user through a room in a zig-zag path. By applying rotational redirection, this path could be bent into a back-and-forth path. The gained knowledge could successfully be used to prevent users of a CAVE system to see the (missing) back wall [17].

Interrante et al. [7] evaluated different locomotion metaphors using translational gain. Subject to this evaluation were four different ways to move through a virtual world: Firstly, regular walking which mapped the real-world locomotion 1:1. Secondly, 10x amplified walking which amplifies virtual translation by the factor 10 in any direction. Thirdly, the so-called *Seven League Boots* metaphor which only amplifies the forward movement by the factor 10, and fourthly a joystick which does not involve real-world walking at all. They found that users prefer the *Seven League Boots* metaphor.

The idea of *Redirected Walking* was later formalized by [23]. Thresholds of suitable gains have been examined [22, 23]. Infinite walking using RDW methods was made possible by [4] who modelled the first dynamic redirection controller. They presented the participants a predetermined, meandering path through the virtual world. Walking on this path, the users could be redirected successfully by applying rotational gain. The amount of applied gain was determined dynamically based on the real-world position of the user. Through these means, the straight meandering path of the virtual world was altered into a circular meandering path in the real world. See section 4 for a formulation of techniques used.

2.2 Reorientation Techniques and Avatars

As it is not always feasible to either use predetermined paths or make infinite walking possible by applying tremendous gains, methods to turn the users around once they reach the borders of the tracked area have been developed [29], the so-called *Reorientation Techniques* (ROT). The basic principle of these methods is to physically turn the user around while maintaining the virtual orientation by applying rotational gain. Peck, Whitton & Fuchs [15] have done an evaluation of different ROTs and found that ROTs using moving distractors in combination with rotational gains are preferred to ROTs which use e.g. verbal commands.

In addition, it was found that people maintain several *rings* of distance limits in interpersonal space ([6], summarized in [10]). According to this, there exist four rings of interpersonal space: public, social, personal and intimate, with distances between the people ranging from $\geq$7.5m to 15cm. This principle is called *proxemics*. Concerning virtual worlds, [1] and [10] found that these personal spaces hold true in virtual worlds as well as in real surroundings. Furthermore, it was found that an increase in anxiety (measured by Skin Conductance Responses, *SCR*) occurred when a single avatar was considered too close and this effect was even stronger for several avatars [10]. Therefore, avatars in VEs might be a very useful distractor, since the interpersonal space rules for humans are well-known and similar rules have been shown to apply in VEs. By going below interpersonal distances the user would allow for the given virtual environment, the user might be redirected by re-establishing comfortable interspace.

2.3 Research on curvature sensitivity

The sensitivity to walking on a curve, both in real and virtual surroundings, has been the focus of previous work [2, 22], especially veering onto a curved path when trying to walk straight without vision [8, 18]. Cratty and Williams [2] used different curved curbs to guide blind walkers. It was the task of the participant to detect whether the followed curb was curved. The experiment showed that the correctness of their responses only rose above chance level for radiuses smaller than 10 feet (approximately 3m). Participants in this study stated that they had the feeling of walking in a more stable way when walking faster.

The veering behaviour of blind and blindfolded people when walking along a straight line was measured by [8]. In one of their experiments, participants were guided on a curved path using a haptic guiding cart and gave a 2-alternative forced-choice (2AFC) feedback. The results showed a detection threshold of approximately 20m radius.

Souman et al. [18] conducted an experiment in which participants were instructed to walk straight in sufficiently large, flat areas with sight (in areas with homogeneous structures like a sandy desert or a dense forest) or blindfolded (on an airfield). It was found that people tend to walk in circles when external cues to direction (e.g., the sun) are absent. When blindfolded, participants walked in circles with a radius as small as 10m, without noticing.

In the context of *Redirected Walking*, [22] have investigated curvature sensitivity in a VE without regard to walking velocity. Participants walked along a straight path for a few meters and were then guided on a curved path. From a 2AFC response, a curvature detection threshold of approximately 22m radius was estimated.

Also, several studies have investigated walking velocity in virtual environments. It was found [12, 19, 24] that people tend to walk slower in virtual reality. Furthermore, [20] found the visual stimulus of virtual walking is perceived as the most natural by the users when scaled up by approximately 20% compared to their actual walking velocity.

3 Experiment 1: Psychophysics of RDW

The results of several research studies [2, 8, 23] suggest there might be an influence of a person's walking speed on their sensitivity to walking on a curved path. To our knowledge, this influence has not yet been researched in detail, so our first experiment aimed to investigate whether there is an effect of walking speed on curvature detection. In contrast to other work [2, 8], we did not have the participants walk blindfolded but used the optical guidance of a HMD-VE to both guide people on a curve and control their walking velocity. The virtual world was rotated with the visual target, so the participants had the impression they were always walking straight in the virtual world. Hence, curvature detection had to be based on body cues (proprioception and inertial cues).

3.1 Method

To measure the curvature detection thresholds of the participants, we had them walk on different curved paths. We measured detection thresholds for three different walking speeds. To control both curvature and walking speed, we modelled a floating sphere in the virtual world. The participants were instructed to follow this sphere at a given distance. They were given feedback on the proper distance to the sphere via its colour. When the actual distance was correct, the sphere was green. If the distance was either too small or too great, the sphere first turned yellow and, for worse distance, later red.

After each trial, the participants were asked whether they had the impression they had walked on a left-hand or a right-hand curve and had to press corresponding buttons on a game pad. The correctness of the response was recorded. Furthermore, the position and orientation of both the sphere and the participant were recorded at a frequency of 60 Hz throughout the trial for subsequent walking analysis.

In a pilot study, we determined a range of tested curvatures from 0.005m^{-1} to 0.05m^{-1}, equalling corresponding circular arcs between 200m and 20m radius. The lowest curvature almost equalled a straight path, while the highest curvature was very distinct. Since users tend to walk slower in virtual environments than they would walk in the real world [12, 19], we determined the tested walking velocities of 0.75, 1.00 and 1.25m/s. The duration of the trials was kept approximately constant (varying between 6 and 7s) for the three different walking speeds. With this duration, all trajectories still fit in our tracking area (11x12m). By randomizing the duration, time was not a strong cue to walking speed. See figure 3 for a graph of the walked curvatures at the maximum speed of 1.25m/s with the average walking duration of 6.5 seconds. Per test series,

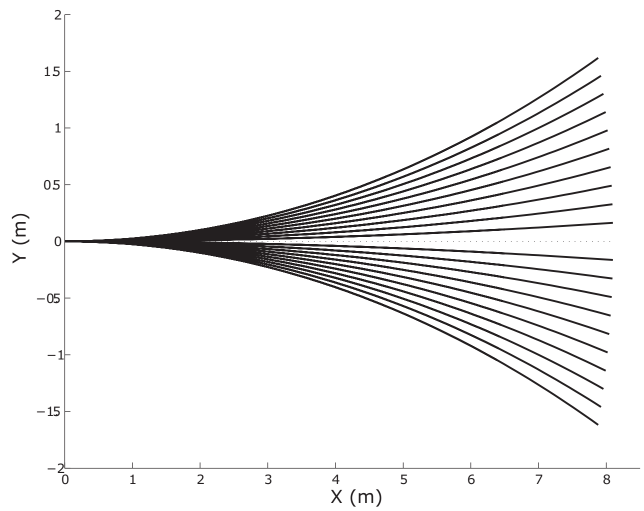

Figure 3: Walked curves (starting at [0,0]) at 1.25m/s and 6.5s duration. Note that since the average walking duration was kept constant for different walking speeds, participants walked different lengths on these trajectories for the different walking speeds.

we repeated each of the tested curvatures 10x in randomized order, each 5x to the left and to the right. Within each of these experiment conditions, we kept the walking velocities constant. To average out a potential learning effect, we repeated the three experiment conditions in reversed order on a different day. We ran each of the six sets of possible condition orders twice, thus requiring 12 participants.

All participants filled out an initial questionnaire before the experiment, asking about their experience with immersive VE. Before and after the experiment, the *Simulator Sickness Questionnaire* (SSQ) of Kennedy et al. [9] was filled out. After the experiment, a presence questionnaire was filled out by all participants about the experienced virtual presence, as well as an experiment-specific questionnaire about the general experience of the test runs.

3.2 Experimental setup

The participant's head position and orientation were optically tracked using 16 *Vicon MX-13* cameras, providing a planar spatial resolution of the tracked object of $\leq$1mm at a frequency of 120Hz. Rigid body tracking was done by *Vicon IQ 2.5*. The scene was rendered on a *Dell Inspirion XPS Gen 2* notebook computer, which was carried by the experimenter during the test runs to lighten the load for the participants. So the participants henceforth only had to carry the tracking helmet, noise-cancelling headphones playing white noise to cover ambient noise, a game pad and the HMD (see figure 4). We used an *eMagin Z800 3D Visor* HMD which could display the scene with a resolution of 800x600 pixels at a refresh rate of 60 Hz. The field of view (FOV) of this HMD is approximately 32x24°. The HMD was built into a pair of ski goggles, so the participants could not see their real-world surroundings. To avoid the potential influence of a rich virtual environment, we used a sparse virtual environment. Before the start of a test run, the sphere, two coloured cylinders and a white line on the floor were presented in the virtual world to allow the participants to properly position themselves. The floor was textured with noise. The partic-

Figure 4: Participant wearing a HMD; his view (target sphere above textured ground plane) is indicated in the inset.

ipants were instructed to walk into the first, semi-transparent cylinder and orient themselves in the direction of the white line. The second cylinder was displayed in some distance, giving feedback by its colour on the proper positioning within the first cylinder (see figure 5). During the test run itself, these auxiliary means were removed so that only a level floor, a plain blue sky and the floating sphere were present (see inset of figure 4).

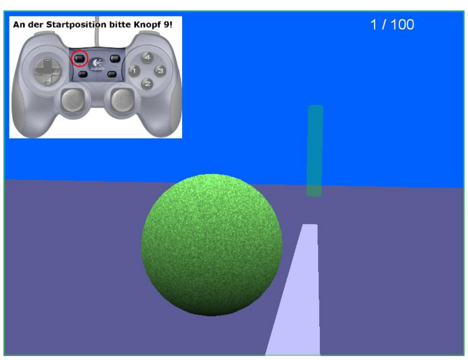

Figure 5: The participant's view while standing in a semi-transparent cylinder; A line on the ground, a sphere and a cylinder for alignment purposes are visible before the start of each test run. During the trial, only the sphere is visible.

As the participants could not see the game pad due to the HMD, a picture of the game pad was displayed in the corner of the visual field when user interaction was necessary, with the keys they could press highlighted (see figure 5).

3.3 Results

The experiment was performed by 12 participants (4♀, 7♂, age 21 – 29, ⌀24.3). During the test runs, we discontinued the experiment for four participants (two due to inability to follow instructions, one due to loss of interest, one went abroad and could not complete the second session). These participants were replaced by 4 additional participants. One participant's data was excluded from analysis as an outlier due to her detection thresholds and PSEs being greater than three standard deviations above the mean.

We filtered out "bad" test runs based on the sideward deviation from the ideal trajectory. With a filter limit of 20cm on the average deviation, 138 (2.09%) of the test runs had to be removed from the data. We checked whether our participants were able to keep the targeted velocity and designated distance to the sphere correctly and found them to be able to keep both velocity (⌀97.3% congruence, see figure 6) and distance (d_{ideal}=0.45m, $\bar{d}$=0.48m) very close to the ideal values. Using the periodic variation in height of the tracked position of the participants' head, we determined the location and time stamps of individual footfalls [26, 27]. Based on that data, we conducted a step analysis and found a linear increase for step length, step velocity and step frequency for increased walking velocities (see figure 6). This pattern is consistent through all test runs of all participants. This is consistent with the biomechanics of natural walking. As the participants had to choose between the responses "Left" or "Right" (2AFC), we received high correctness for very distinctive curvatures but chance level for very low curvatures. For the data analysis, we inverted the correctness of the right-hand curves in order to obtain a sigmoid distribution of the data. The resulting data semantically describes the probability of a positive response if we would have asked the question "Did you have the impression you walked on a left-hand curve?". We determined the ratio of positive responses and fitted a psychometric function to the results using the psignifit toolbox [28] for each walking velocity (see figure 7). This was done separately for the data of each participant.

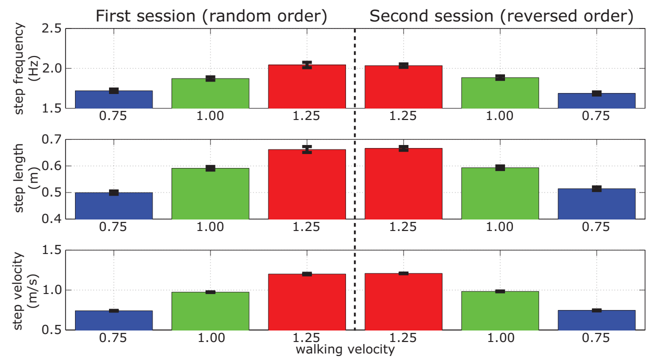

Figure 6: Step analysis (all 6 conditions) for 11 participants. Bars denote one standard error of the mean.

For the overall results, we determined the participant's detection threshold and point of subjective equality (PSE) for each velocity. The detection threshold is represented by the value at which participants are on average able to recognize the direction of the walked curve correct in 75% of the test runs. The PSE represents the calculated value where participants perceive the middle between the two alternatives of an experiment. In this case, the middle of left-hand and right-hand curves is a straight line. If there was no bias of the participants to careen to a specific side, the calculated PSE value should be at zero curvature for 50% response correctness.

We performed a repeated-measures ANOVA (Greenhouse-Geisser corrected for asphericity) with PSE and threshold. For the PSE values, we found no significant deviation from zero, F(1.088, 10.877)=0.865, p=0.382, indicating that there was no bias of the participants to a specific side. As the main measurement of the experiment, we analysed the detection thresholds and found a significantly higher detection threshold for the slowest tested walking velocity, F(1.053,10.532)=13.573, p=0.004. The results for all participants are plotted in figure 8. For 0.75 m/s, we found a detection

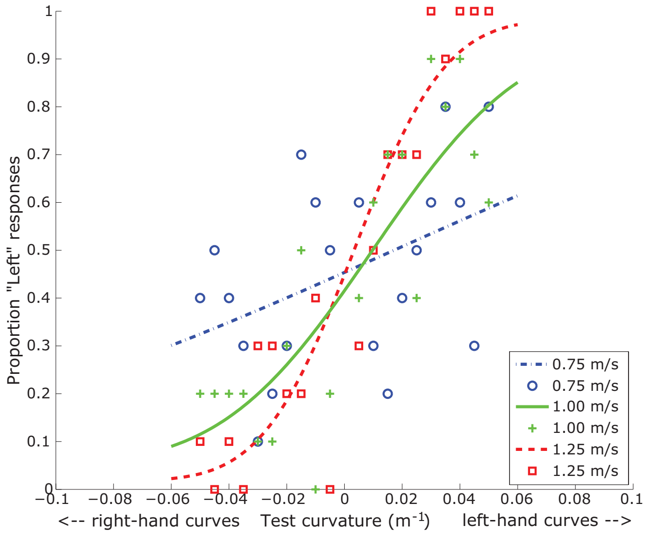

Figure 7: Fitted psychometric functions (lines) and actual data (dots) for one participant's data

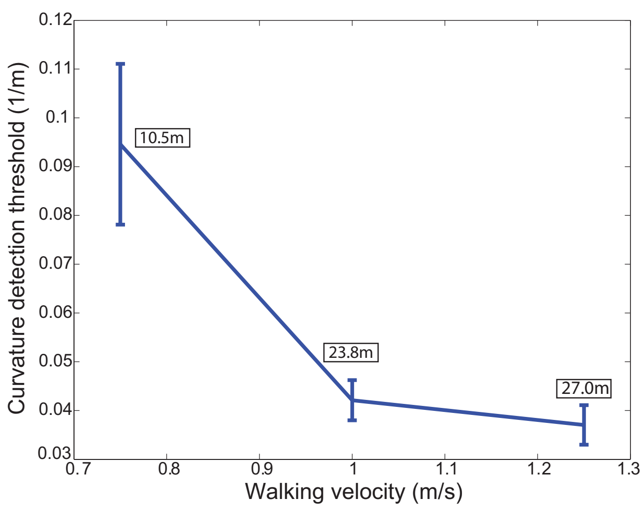

Figure 8: Curvature detection thresholds for all participants (corresponding radius in boxes, bars denote standard error)

threshold of approximately 0.095m^{-1}, which represents a circular arc of 10.5m radius. In contrast to this, we found higher sensitivity for faster walking velocities, approximately 0.04m^{-1} (radius of 23.8m) for 1.00m/s and approximately 0.038m^{-1} (radius of 27.0m) for 1.25m/s.

The evaluation of the SSQ total scores revealed an increase of 11.53 on average with an interquartile range (IQR) of 5-20. This is consistent with literature related on Simulator Sickness in HMD set-ups ([3]: 12-17, [5]: 14.5 and [11]: 16.6).

3.4 Discussion

In this experiment, we could show that people are significantly less sensitive towards walking on a curved path when walking slower than they are at faster walking speeds. This could be of great use for applications which use *Redirected Walking* to extend the walkable space beyond the dimensions of the actual tracking area space, especially since it has been shown that people walk slower in virtual environments [12, 19].

4 Implementation of a Dynamic RDW gain controller for free exploration

We used the gained knowledge from Experiment 1 and modelled a RDW controller extending the controller described by [4] and [20]. We implemented most of the redirection techniques that were described but did not make use of time-dependent translational gain and displacement gain (cf. [20]) to avoid direct translational shifts without corresponding translational user movement.

The head rotation was scaled up or down with respect to the spatial position and head orientation of the participant (see section 4.3) The translational movement was scaled up by a factor of 2. As related work has shown [22, 7], this gain represents only a moderate manipulation to improve redirection. Also, we implemented a curvature gain controller which introduces rotation to the virtual camera with respect to the translational movement of the user. The curvature gain was also influenced by the *Positional overall gain* (see section 4.3) and was either based on a static factor or dynamically adjusted depending on the actual walking speed (see section 4.1). Moreover, we implemented a time-dependent rotational gain, which constantly rotated the virtual world by 1°/s and thus allowed for a small, yet constant redirection[1]. We extended this state-of-the-art controller by four modifications which are depicted in detail in the following four sections.

4.1 Static and dynamic curvature adjustment

For our dynamic and static curvature adjustment, we chose a curvature gain which is higher than what was perceptually noticeable in Experiment 1. In Experiment 2, we used a rich realistic world and hypothesized that we could apply higher gains than in a sparse virtual world. As our static gain value, we chose 0.13 m^{-1}. This curvature gain in combination with our positional controller (cf. 4.3) resulted in an average curvature gain which was close to our curvature detection thresholds found in Experiment 1, and also is suggested by previous research [22]. For our dynamic curvature adjustment, we applied higher gains for lower walking velocities ($v<0.75$m/s, curvature gain = 0.2 m^{-1}) and applied lower gains for higher velocities ($v>1.25$m/s, curvature gain = 0.13 m^{-1})). For velocities between 0.75 and 1.00 m/s, we used the following formula: $f(v)=-0.2v+0.35$. For velocities between 1.00 and 1.25m/s, we used $f(v)=-0.04v+0.09$. These formulas were motivated by the results from Experiment 1. The dynamic curvature gain calculation in combination with the positional controller for normal walking should also result in curvature gains close to our curvature detection thresholds found in Experiment 1.

4.2 Reorientation technique

We agree with [4] that it is theoretically impossible to completely redirect users to stay within the given walking area when allowing free walking. There is always the possibility that a user ignores the given distractors, shows a walking behaviour that is particularly hard to redirect (especially long straight walking with low head rotation) and takes the wrong turns at the wrong time. So there is the need to introduce a reorientation technique (ROT) as the ultimate means to prevent users to leave the walking area. Based on the findings of [29], we decided to use a ROT that displays a stop sign to the users and *freezes* the virtual world (see figure 9). The users need to be instructed beforehand to stop walking when the stop sign is displayed and to turn around until the stop sign disappears. The virtual world is then *unfrozen* and the user is able to continue walking in the direction they intended.

[1]The value of 3° proposed by [16] was subjectively too strong during the pilot study and thus reduced.

Figure 9: Reorientation technique using a stop sign

4.3 Gain controller: Position in tracked space

According to the findings of [4], it is disadvantageous to redirect the user into corners of the real world area. Therefore, we attempt to redirect the user to walk on a circle around the centre of the real-world walking area. To achieve this, we created two functions. The first function watches the heading angle of the user with respect to the angle towards the centre of the walking area and penalises non-tangential heading angles. The second function returns an *overall gain* based on the real-world position and orientation of the user. This function applies higher gains when the user is both close to *and* facing a wall or the centre of the walking area. A graph of the return values for an exemplary heading angle of 45° is shown in figure 10; in order to avoid extreme rotational gains, the depicted raw gain is clipped at 1.5.

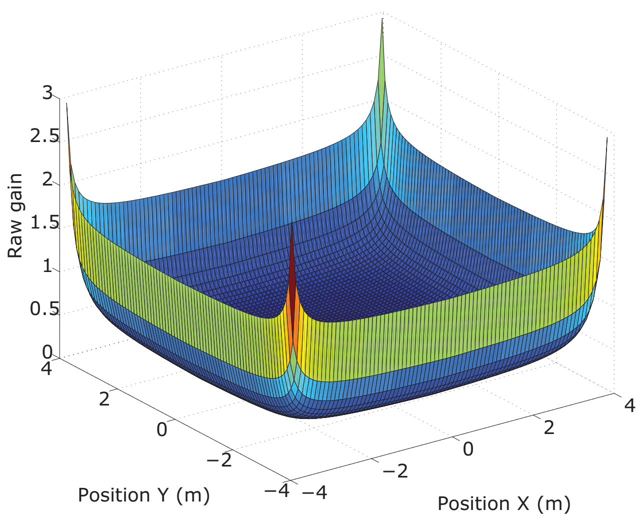

Figure 10: Position-based gain determination for 45° heading angle

4.4 Avatar distraction and redirection support

As it has been shown that the principles of personal space (cf. section 2.2) also hold true in VEs [10, 1] and the limits of the personal space can also be violated by avatars, we suggest it could also be possible to use avatars to support underlying RDW algorithms by influencing the participant's walking behaviour. Furthermore, presenting avatars in the virtual world populates the space, leading to higher realism and potentially increasing the user's experience of virtual presence.

We created an avatar component for the RDW controller that makes use of two types of avatar redirection (see figure 11). One avatar is created to walk in front of the user with its distance depending on the user's walking velocity. For faster velocities, the avatar is walking closer in front of the user, attempting to slow the user down and thus allowing higher curvature gains according to the findings of the first experiment. The second avatar algorithm places an avatar directly outside the user's viewing frustum when the user is approaching the boundaries of the walking area. By walking into the scene, hereby intersecting the straight path of the user, this avatar aims to initiate collision-avoiding behaviour of the user (see figure 11). This additional movement, especially head rotation, can potentially be exploited by the underlying RDW algorithms, thus leading to additional redirection. When passing an avatar, there is the potential that the user turns his head towards the walking-by avatar, hereby performing rotation which also could be redirected.

Figure 11: The two avatar concepts (slowing down and intersecting) which were used for redirection support

5 Experiment 2: Evaluation of dynamic RDW

The aim of the second experiment was twofold. First, we aimed to evaluate the findings of the first experiment in a rich virtual world. Therefore, we used the described free-walking controller which adjusts applied curvature gain with respect to the instantaneous walking velocity of the user. Second, we aimed to receive first data for the newly-created controller for Avatar Redirection and evaluate the effect it has on the success of redirection.

5.1 Method

To measure the effectiveness of the *Dynamic Curvature Gain Controller* and the *Avatar Redirection Controller*, we had our participants explore the virtual model of a city while walking around in a real-world experimental area of 8.6x8.6 meters. In a between-subject experimental design, we tested the four conditions of both controllers enabled or not. While walking, we measured the walked distance which was covered before the participants reached the boundaries of the experimental area and thus had to be reoriented using the ROT.

Each participant walked for one kilometer in the VE. A repetition test run was conducted consecutively after a break in between. In the same manner as during the first experiment, all participants filled out an initial questionnaire, one SSQ each before and after the experiment, a presence questionnaire and an experiment-specific questionnaire.

5.2 Experimental setup

In this experiment, we used an *nVisor SX60* HMD with a resolution of 1280x1024 pixels and a refresh rate of 60Hz. The diagonal FOV of this HMD is 60°. The notebook computer, a *Dell Precision*

M6400, was again carried by the experimenter to lighten the load of the participant. As the optical markers for the tracking system (16 *Vicon MX-13* cameras) are attached to the HMD, the participants only had to wear the HMD. For this experiment, we used the virtual model of Tübingen, Germany[2] which is approximately 500x150m in size. The participants were instructed to walk around in the city freely and to stop as described when seeing the stop sign.

When the avatar controller was enabled, there was one avatar walking in front of the user and one intersecting from the side (cf. section 4.4). We used four different avatars from *RocketBox GmbH* (*sportive01_f*, *sportive04_f*, *casual09_m* and *casual29_m* with the key-framed animations *idle1* and *walk*). As the slowing-down avatar was constantly visible, its appearance was always *sportive01_f*, whereas the appearance of the intersecting avatar was randomized (see figure 11) between the remaining avatars.

5.3 Results

The experiment was successfully completed by 32 participants (17♀, 15♂, age 19-51, ⌀ 27.26). Three additional participants (each in different experimental conditions) decided to cancel the experiment due to motion sickness. As the main measuring unit, we determined the distances the participants could walk before reaching the boundaries of the experimental area (seeing the stop sign). Furthermore, we determined the number of stop sign occurrences, the necessary turning angle to overcome the reorientation phase, the time which was spent for reorientation and the average applied gain. As the obverse of applying more gain is a higher probability of Simulator Sickness, we also evaluated the SSQs.

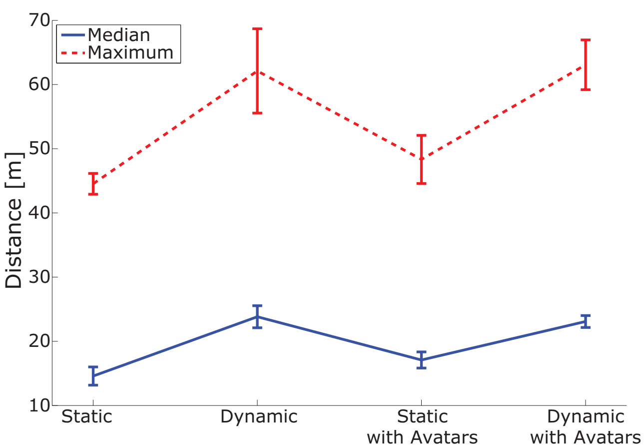

Figure 12: Measured free walking distances of 32 participants for the four conditions. Median and maximum distances are shown, bars denote standard error.

The results show a highly significant difference in the mean walked distance (see figure 12) between the stop signs for conditions with static and dynamic curvature gain. While participants reached the boundaries of the experimental area after approximately 15m in average for conditions with static curvature gain, the application of dynamic curvature gain allowed them to walk for approximately 22m before reaching these boundaries. We conducted a one-way ANOVA on these distances and found significance, $F(1,30)=83.862$, $p=\leq 0.001$. For the maximal walked distances, the significance is even higher, $F(1,30)=42.104$, $p \leq 0.001$. The average maximal walking distance for all participants was approximately 42m for static curvature gain and approximately 62m for dynamic curvature gain. For avatar redirection, the results show no significant improvement on the stop lengths, $F(1,31)=0.08$, $p=0.928$. Part of this might originate from the fact that the participants walked relatively slow (⌀ ≈ 0.6m/s). This velocity was below the action threshold of the slowing down avatar which was virtually walking in front of the participants. The slow walking speed could have been caused by the accelerated optical flow by the increased translational gain but also by the fact that they were instructed to just browse through the virtual city instead of having to solve a task as quickly as possible.

An one-way ANOVA comparing the SSQ values showed no significant increase neither when using the higher dynamic gains, $F(1,31)=1.185$, $p=0.285$, nor when showing avatars, $F(1,31)=0.506$, $p=0.483$. The SSQ scores of this experiment are similar to the values we found in our first experiment and also can be found in literature [3, 5, 11].

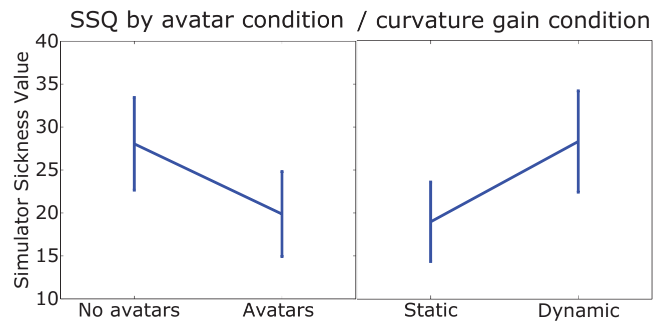

Figure 13: Total SSQ values for the two tested parameters. Bars represent the standard error of the mean.

We checked whether there is an effect on the participant's gender. We conducted an one-way ANOVA on the stop lengths and found no significance, $F(1,31)=1.03$, $p=0.32$. Also, we did not find a difference for the total SSQ value, $F(1,31)=1.09$, $p=0.31$.

5.4 Discussion

In this second experiment, we conducted a validation of our findings in Experiment 1 and found a highly significant improvement on the distance which could be walked without having to be stopped by a reorientation technique when using our dynamic gain controller. This did not come at the cost of an increase of SSQ values when using the higher, dynamically adjusted curvature gain. Although the curvature gains we used in the second experiment were higher than the detection thresholds we found in the first experiment, the participants did not state the curvature redirection when we asked them about possible explanations for redirection in the experiment-specific questionnaire. Partly, this might be explained by the increased visual stimulus of a realistic scene compared to an artificial experimental set-up. However, further research would need to be conducted to investigate their sensitivity in our second experimental setup.

The newly created concept of avatar redirection did not lead to a significant rise in the walkable distance. So for future work, we will use the gained knowledge and design a modified avatar distractor algorithm. As it is described by [10], the effect of avatar proxemics is increased by multiple avatars. Also, presenting a group of avatars to the user makes it potentially easier to redirect them into a desired direction or even completely stop them from walking further, hence potentially being able to avoid non-realistic reorientation techniques (e.g. stop sign).

6 Conclusions

In a VR experiment, we found that people are significantly less sensitive to walking on a curve when walking slower. In the context of *Redirected Walking*, these findings can be used to achieve higher

[2]http://virtual.tuebingen.mpg.de

redirection for slower walking without the user noticing being redirected more strongly. These findings lead to the conclusion that there is a practical value of these results for any RDW application that makes use of curvature gain. In addition, we expect these results to also be interesting to other areas of research (i.e. biomechanics, psychology).

We implemented a dynamic curvature gain controller for RDW which includes reorientation techniques, and therefore provides the ability to allow the user to freely explore a space for an unlimited distance without the aid of the experimenter. We used this implementation in a second experiment in combination with a large virtual city model and validated the usefulness of the dynamic curvature gain based on walking speed. We demonstrated this by evaluating the distance walked before requiring a redirection technique (stop sign) and found that with dynamic curvature gain, participants on average could walk further. The average walking distance between reorientations increased from 15m for static curvature gain to 22m for dynamic curvature gain. The maximal walked distance rose from 42m to 62m. Most important, this increase in walkable distances did not come at the cost of a significantly increase in simulator sickness. In addition, we made a first attempt at using avatars as a distractor. Further research can now be done with our new method of evaluating redirected walking and our dynamic gain controller with improved virtual characters. This research extends what is possible in RDW and provides interesting perceptual results for scientists interested in the sensitivity of humans to walking on a curved path.

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