Velocity-Dependent Dynamic Curvature Gain for Redirected Walking

Christian T. Neth, Jan L. Souman, David Engel, Uwe Kloos, Heinrich H. Bülthoff and Betty J. Mohler

Abstract—Redirected walking techniques allow people to walk in a larger virtual space than the physical extents of the laboratory. We describe two experiments conducted to investigate human sensitivity to walking on a curved path and to validate a new redirected walking technique. In a psychophysical experiment, we found that sensitivity to walking on a curved path was significantly lower for slower walking speeds (radius of 10 meters versus 22 meters). In an applied study, we investigated the influence of a velocity-dependent dynamic gain controller and an avatar controller on the average distance that participants were able to freely walk before needing to be reoriented. The mean walked distance was significantly greater in the dynamic gain controller condition, as compared to the static controller (22 meters versus 15 meters). Our results demonstrate that perceptually motivated dynamic redirected walking techniques, in combination with reorientation techniques, allow for unaided exploration of a large virtual city model.

Index Terms—Virtual Reality, Redirected Walking, Virtual Locomotion, Curvature Sensitivity, Avatars

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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 Steinicke et al. [1]). This dominance of vision is exploited in *Redirected Walking* in order to increase the size of Virtual Environments which can be explored on foot. Modern computer graphics provide a particularly convenient means to manipulate the visual input to the user and enhance the feeling of presence in Virtual Environments.

The aim of *Redirected Walking* (RDW, first described by Razzaque et al. [2]) 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 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 1). As long as the induced curvature is small enough, this manipulation is not noticed by the users. Related work has successfully used RDW to allow users to walk arbitrarily far through virtual

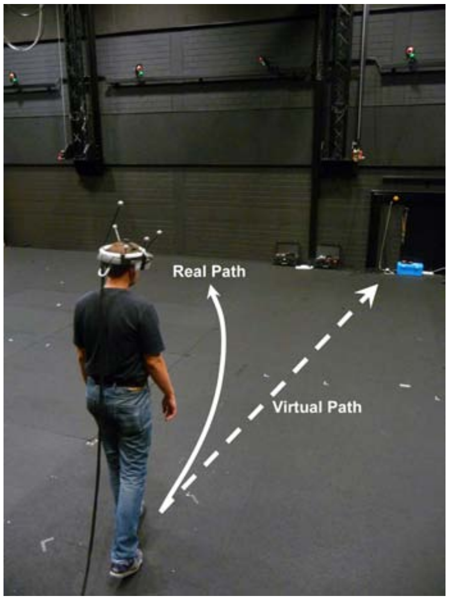

Fig. 1. The principle of Redirected Walking

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worlds of greater dimensions than the available tracking area [3], [4]. However, both of these previous methods had serious limitations for use: the path was predetermined (Engel et al. [3]) or the person had to stop very frequently to reorientate when they reached the boundaries of the space (Williams et al. [4]).

In this paper, we present two distinct experiments with the aim of improving the current-state-of-the-art in RDW algorithms towards unaided free exploration of virtual worlds in confined spaces. In the first experiment, we used psychophysics methods to investigate the sensitivity of humans to walking on a curved path at various walking speeds using a light-weight HMD setup. In the second experiment, we first extended a state-of-the-art dynamic gain controller for RDW. Our two main additions were to make the gain controller dependent on the speed of the user, and to add avatars as a possible tool for additional redirection. Finally, we suggest a new measure for RDW techniques: the distance a participant can walk before needing to use an unnatural reorientation technique. In our second experiment, we demonstrated that participants could walk unaided for an entire virtual kilometre in a small tracking hall by using the extended dynamic gain controller.

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 describe related research on curvature sensitivity. Second, we delinerate existing RDW techniques. Finally, we introduce reorientation techniques (ROTs), used when RDW algorithms are not sufficient.

2.1 Research on curvature sensitivity

The sensitivity to walking on a curve, both in real and virtual surroundings, has been the focus of previous work [5], [6], especially veering onto a curved path when trying to walk straight without vision [7], [8]. Cratty & Williams [5] 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 3 m). Interestingly, participants in this study felt themselves to be 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 Kallie et al. [7]. 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) response on the direction of curvature. The results showed a detection threshold of approximately 20 m radius.

Souman et al. [8] conducted an experiment in which participants were instructed to walk straight in sufficiently large, flat areas with vision (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 10 m, without noticing.

In the context of *Redirected Walking*, Steinicke and colleagues [6] 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 22 m radius was estimated.

Concerning walking velocity in virtual reality, several studies have reported that people tend to walk slower in virtual environments [9], [10], [11]. Additionally, Steinicke et al. [12] found the visual consequences of walking through a virtual environment are perceived as most natural when scaled up by approximately 20% compared to their actual walking velocity.

2.2 Redirected Walking setups

Redirected Walking has first been described by Razzaque, Kohn & Whitton [2]. In their study, 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 same technique was successfully used to prevent users of a CAVE system from seeing the (missing) back wall [13].

Interrante et al. [14] evaluated different locomotion metaphors using translational gain. Subject to this evaluation were four different ways to move through a virtual world: Firstly, regular walking with a 1:1 mapping between motion in the real world and the virtual one. Secondly, 10x amplified walking which amplified virtual translation by a factor 10 in any direction. Thirdly, the so-called *Seven League Boots* metaphor which amplified only the forward movement by a factor 10, and fourthly a joystick which did not involve any real-world walking at all. They found that users preferred the *Seven League Boots* metaphor.

The idea of *Redirected Walking* was formalized by Steinicke and colleagues [1], and perceptional thresholds for suitable gains have been examined in following work [6], [15]. Infinite walking, albeit on a predefined path, using RDW methods was made possible by Engel et al. [3] 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.

Suma and colleagues [16], [17] have presented a different approach to redirect users when the accuracy of the virtual world does not play a strong role. Exploiting the phenomena of *Change Blindness*, the geometry of the virtual world could be altered without being noticed by the users. Doors in corners were flipped to the opposite wall, leading to a 90° redirection each time.

2.3 Reorientation Techniques

It is not always feasible to use predetermined paths or to apply very high gains. Hence, methods to turn the users around once they reach the borders of the tracked area have been developed by Williams et al. [4], the so-called *Reorientation Techniques* (ROTs). The basic principle of these methods is to make users turn around physically or relocate the user while maintaining the virtual position and orientation. Williams et al. [4] presented three different methods to achieve this. Two of them involve 'freezing' the virtual world upon reaching the limits of the walking space. In the first method, the users were instructed to walk backward until they reached a position allowing enough clearance to walk forward again. The second and third methods achieve physical turnaround by applying rotational gains: The so-called 'Freeze-turn' applies a gain of zero, leading to no virtual rotation while the user is turning around physically. In contrast to this, the third method applies a gain of two. By instructing the users to perform one complete rotation, the user has the impression of rotating once completely yet turns by only 180° in the real world. Williams and colleagues [4] conducted a study which compared the efficacy of these three techniques and measured the participants' turning errors and latencies. Turning error was lowest for the method where participants were asked to walk backward, while the latency of pointing was smallest in the condition where the gain of two was used.

Peck et al. [18] have done an evaluation of different ROTs. Unlike Williams et al. [4], the virtual world was never frozen but participants were instructed to stop and rotate upon reaching the boundaries of the walking space. Rotational gains were applied in several ways. This study reported that a combination of moving distractors (e.g. a butterfly) and rotational gains was experienced as more natural and preferred to for example ROTs which used verbal commands only.

3 EXPERIMENT 1: CURVATURE SENSITIVITY AND WALKING SPEED

The results of several research studies suggest that there might be an influence of a person's walking speed on their sensitivity to walking on a curved path [5], [7], [15]. To our knowledge, this influence has not yet been studied in detail, so our first experiment aimed to investigate whether walking speed affects curvature detection. In contrast to the work of Cratty & Williams [5] and Kallie et al. [7], 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.

3.1 Method

To measure curvature detection thresholds, we had participants walk on paths with different curvatures. Detection thresholds for three different walking speeds were measured. 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 ($d_{target} = 0.45m$). They received feedback on the proper distance to the sphere via its colour. When the actual distance was very close to the target distance, the sphere was green. Following a linear change in colour, the sphere first turned yellow ($d_{actual} \leq d_{target} \pm 0.5 \times d_{target}$) and then, for larger displacements, red (linear change in colour until $d_{actual} = 2 \times d_{target} = 0.9m$). The virtual world was rotated with the sphere in such a way that participants always had the impression that they were walking along a straight line in the virtual world. Hence, curvature detection had to be based on body cues only (proprioception and inertial cues).

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

In a pilot study, we determined an appropriate range of curvatures from 0.005 m^{-1} to 0.05 m^{-1}, corresponding to circular arcs with a radius between 200 m and 20 m. The lowest curvature almost equalled a straight path, while the highest curvature was distinct. Since users tend to walk slower in virtual environments than they would walk in the real world [9], [10], [11], we used walking velocities of 0.75, 1.00 and 1.25 m/s, which are all slower than the normal average walking speed of about 1.4 m/s [19], [20]. Trial duration was kept approximately constant (varying randomly between 6 and 7 seconds) for the three different walking speeds. With this duration, all trajectories still fit in our tracking area (11 m × 12 m). This randomization was done so that participants could not easily predict when the sphere stopped.

Per block, we repeated each of the tested curvatures 10× in randomized order, each 5× to the left and to the right, leading to 100 (10 × 5 × 2) test runs per block. Within each of these experimental conditions, we kept the walking velocities constant. The order of the walking velocity conditions was varied across participants, and all three conditions were repeated in reversed order on a different day to balance potential order effects. Consequently, participants completed 600 trials (100 × 3 × 2) in total which were equivalent to a total walking distance of approximately 3.9 kilometres. Including breaks, the experiment took approximately 6 hours per participant, 3 hours on each day. Before and after each session, the *Simulator Sickness Questionnaire* (SSQ) of Kennedy et al. [21] was filled out as well as an experiment-specific questionnaire about the general experience of the test runs after the experiment. The experiment was performed by 12 participants (5♀, 7♂, age 21 – 29, ⌀24.3).

3.2 Experimental setup

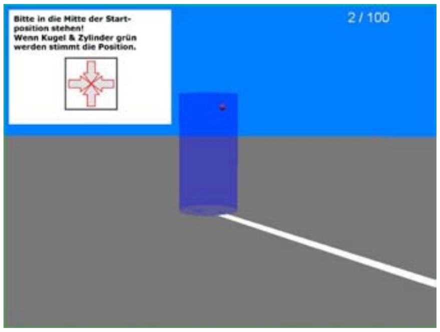
The participant's head position and orientation were optically tracked using *Vicon IQ 2.5* and 16 *Vicon MX-13* cameras, providing a planar spatial resolution of the tracked object of ≤ 1 mm at a frequency of 120Hz. The scene was rendered on a *Dell Inspirion XPS Gen 2* notebook computer, which was carried by the experimenter during the test runs to lighten the load for the participants. The participants only had to wear or carry the tracking helmet, noise-cancelling headphones playing white noise to mask ambient noise, a game pad and the HMD (see figure 2). Due to the planned experimental time of approximately 45 minutes × 6 blocks (three per day), we chose to use a lightweight HMD (eMagin Z800 3D Visor, 220 g). The HMD had a field of view (FOV) of 32° × 24° and displayed the scene with a resolution of 800 × 600 pixels at 60 Hz. 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 (see figure 3). While the floor was textured with a random blurred pattern during the test runs, it was a uniform grey during the positioning phase. The participants 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 at a distance of 14 m, giving feedback by its colour on the proper positioning within the first cylinder and indicating the walking direction (see figure 3 and 4). During the test run itself, these orientation instructions were removed so that only a level, randomly textured floor, a uniform blue sky and the floating sphere were present (see inset of figure 2).

Fig. 2. Participant wearing a HMD; his view (target sphere above textured ground plane) is indicated in the inset.

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 4).

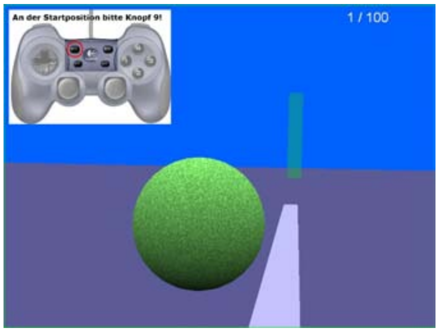
3.3 Results

Trials in which the average absolute deviation from the target trajectory exceeded 20 cm were discarded from further analysis (148 trials, or 2.2%). For the remaining trials, participants' responses on the curvature of the path were converted to the proportion of 'rightward' responses for each curvature tested. To these proportions, a cumulative normal distribution was fitted for each walking velocity, using the psignifit toolbox [22] (see figure 5). One participant's data were excluded from analysis as an outlier (detection thresholds and PSEs greater than three standard deviations above the mean). From the fitted psychometric functions, we determined the participants' detection thresholds and points of subjective equality (PSE) for each walking velocity. The detection threshold is defined as the value at which participants were on average able to recognize the direction of the walked curve correctly in 75% of the test runs. The PSE represents the curvature value where the participants are equally likely to report left and right curvature. Deviation of the PSE from 0 indicates



Bitte in die Mitte der Start-position stehen!
Wenn Kugel & Zylinder grün werden stimmt die Position.

Fig. 3. A line on the ground, a sphere and a half-transparent cylinder marking the starting position are visible before the start of each test run.



An der Startposition bitte Knopf 9!

Fig. 4. The participant's view while standing in the start cylinder. During the trial, only the sphere was visible.

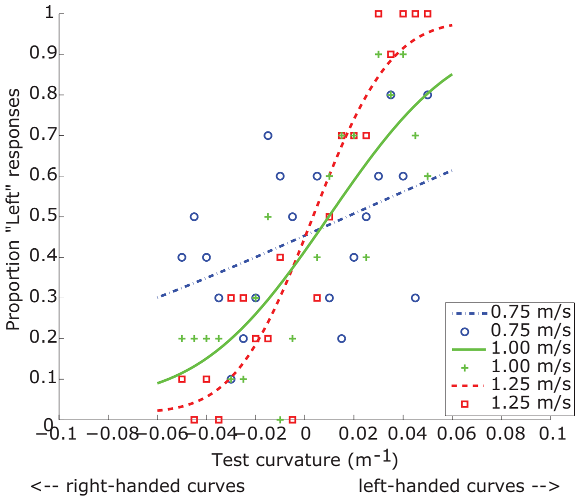


Fig. 5. Fitted psychometric functions (lines) and actual data (dots) for one participant's data

a directional bias (either leftward or rightward, depending on the signal of the deviation).

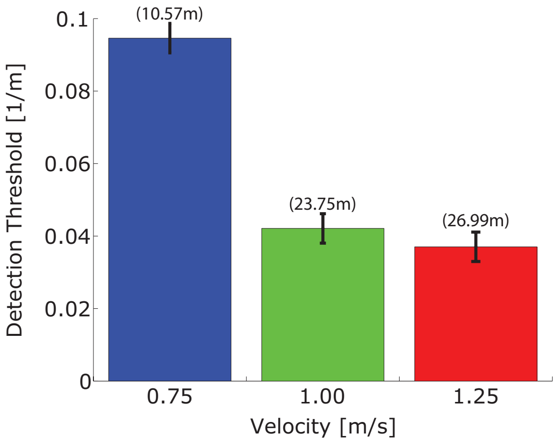


Fig. 6. Curvature detection thresholds across all participants (corresponding radius in brackets, bars denote standard error of the mean)

None of the three PSE values differed significantly from zero, indicating that participants did not exhibit a bias to a specific side ($PSE_{0.75} = 0.010m^{-1}, SE = 0.013m^{-1}; PSE_{1.00} = 0.002m^{-1}, SE = 0.004m^{-1}; PSE_{1.25} = -0.002m^{-1}, SE = 0.004m^{-1}$). A repeated-measures ANOVA (Greenhouse-Geisser corrected for asphericity) did not show a significant effect of walking speed on PSEs, $F(1.084, 10.842) = 0.763, p = 0.412$. Moreover, the overall mean PSE did not differ significantly from zero (intercept test, $F(1,30) = 0.448, p = 0.508$). As the main measurement of the experiment, we analysed the detection thresholds of walking on a curve. The average results for all participants are plotted in figure 6. For 0.75 m/s, we determined a detection threshold of approximately 0.095 m^{-1}. In contrast to this, we found lower values (reflecting higher sensitivity) for faster walking velocities, approximately 0.042 m^{-1} for 1.00 m/s and approximately 0.037 m^{-1} for 1.25 m/s. We performed a repeated-measures ANOVA (Greenhouse-Geisser corrected for asphericity) with walking velocity as independent and threshold as dependent variable, and found significantly different detection thresholds between the tested walking velocities, $F(1.053, 10.532) = 13.573, p = 0.004, \eta_p^2 = 0.576$. In order to more specifically assess the difference between the tested velocities, we performed a Fisher's LSD post-hoc comparison. It revealed a significant difference between the slow velocity and both medium, $p = 0.007$, and fast, $p = 0.002$, walking speed. We did not find a significant effect between the medium and fast conditions, $p = 0.091$.

We fitted circular curves to the trajectories and determined the deviation between the actual walked and the targeted curvature. Figure 7 shows the trajectories walked by one participant at 1.25 m/s as an example. Figure 8 shows the correspondence of actual curvature of the walked trajectories to the curvature of the target sphere for all participants. Based on the fitted curves, we determined the ratio between actually walked and given trajectories.

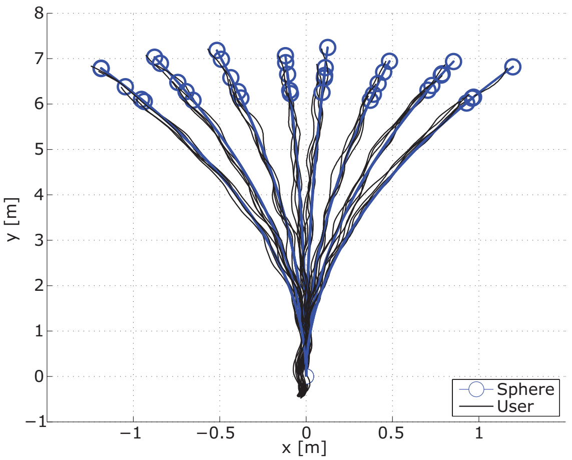


Fig. 7. Exemplary walked trajectories from ±0.05 m^{-1} (20 m radius) to ±0.005 m^{-1} (200 m radius) at 1.25 m/s for one participant.

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 9) and distance (d_{target}=0.45 m, $\bar{d}$=0.48 m) very close to the target values. Using the periodic variation in the vertical position of the participants' head, we determined the location and time stamps of individual footfalls [23], [24]. We conducted a step analysis and found a linear increase for step length, step velocity and step frequency for increasing target walking velocities (see figure 9). This pattern is consistent through trials of all participants. This is consistent with the biomechanics of natural walking.

Analysing the tracked orientation of the participant's head, we investigated whether there is a difference in head rotation for different walking speeds. Therefore, we summed up the difference between peak values of the yaw angle and subtracted the baseline rotation given by the

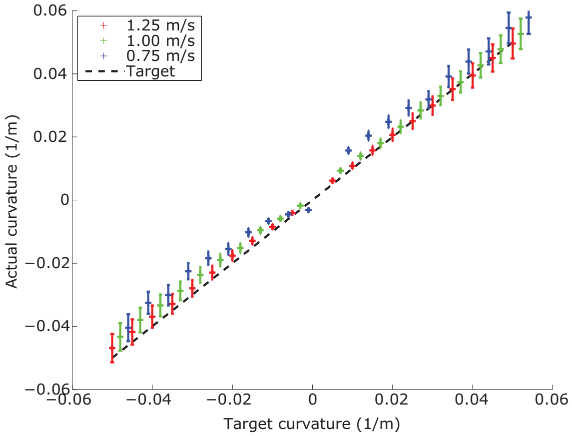


Fig. 8. Deviance between actually walked and targeted curvature. Values are slightly shifted along the x-axis for clarity (positive shift of 0.001, and 0.002 1/m for the 1.00 and 0.75 m/s condition, respectively). Bars denote one standard error of the mean.

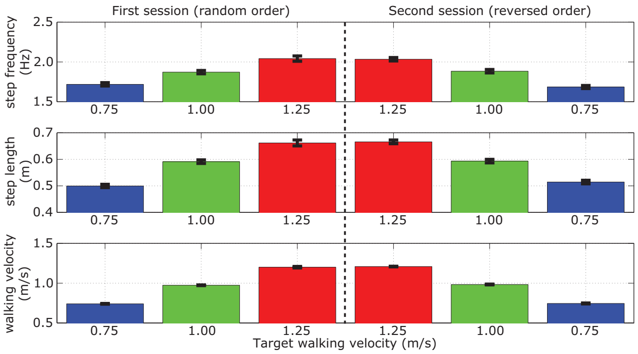


Fig. 9. Step analysis (all 6 conditions) for 11 participants. Bars denote one standard error of the mean.

experimental trajectory. We conducted a repeated-measures ANOVA on the total amount of the participants' head rotation as a dependent variable and did not find a significant difference, $F(1.789, 10) = 2.067, p = 0.159$.

The evaluation of the SSQ total scores collected before and after the experiment revealed an average increase of 11.53 points during the experiment with an interquartile range (IQR) of 5-20. This is consistent with literature related on Simulator Sickness in HMD set-ups (Ehrlich [25]: 12-17, Hakkinen et al. [26]: 14.5 and Mehlitz [27]: 16.6).

3.4 Discussion

In this first experiment, we demonstrate that people are significantly less sensitive towards walking on a curved path when walking slower. This means that when a person in virtual reality is walking at a slow walking speed (0.75 m/s) the curvature used for redirection can have a radius of approximately 10 meters, which fits into a significantly smaller space than the curvature (radius of approximately 23-24 meters) needed for faster walking speeds (1.0 and 1.25 m/s). These results are consistent with previous and similar research which shows curvature detection thresholds ranging from 10-28 meters [6], [7], [8].

Why would people be worse at detecting walking on a curve when walking at a slower speed? Though, in the present experiment, we did not directly address this question, we can analyse the walking trajectories of participants to determine if something about the way people walked might explain this difference in perceptual thresholds. First, we looked at how much participants deviated from the target curvature. We found that for all three walking speeds, deviations from the curvature of the target trajectory were similar. Further, we looked at biomechanical properties to see if they are consistent with what is expected when people walk at a given speed. We found no deviations from the literature in factors such as step length, step frequency and step velocity. Finally, we looked at the total amount of head rotation while walking a specific curve. We find no indication in the walked trajectories which help us to increase our understanding as to why people are less able to detect a curved walked path when walking slower. In this experiment, we kept the walking time relatively constant, varying instead the walked distance as a function of walked velocity. A variation of this experimental design might be to keep the walking distance constant and vary the walking time. We leave it for future work to investigate whether distance and/or time travelled influences curvature detection.

The results from this first experiment 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 [9], [10], [11]. Additionally, since people often walk at different speeds, an algorithm which dynamically alters the curvature gain based on walking speed would be potentially advantageous.

4 IMPLEMENTATION OF A DYNAMIC RDW GAIN CONTROLLER FOR FREE EXPLORATION

We used the results from Experiment 1 to model a RDW controller which extends the dynamic gain controller described by Engel et al. [3] and Steinicke et al. [12]. We implemented most of the state-of-the-art redirection techniques (rotational, translational, curvature and time-depended rotational gain). However, we did not use time-dependent translational gain or displacement gain (cf. Steinicke et al. [12]) to avoid direct translational shifts without corresponding translational user movement.

The virtual head rotation was scaled up or down (*Rotational Gain*) with respect to the spatial position and head orientation of the participant (see section 4.2). The translational movement (*Translational Gain*) was scaled up by a factor of 2. As related work by Steinicke et al. [6] and Interrante et al. [14] has shown, even this doubling of locomotion represents only a moderate manipulation to improve redirection as it was found that humans underestimate the distance when walking in VR ([28], [29], topic summarized in [30], overview also in [6]). Also, we implemented a

Curvature Gain controller which introduces rotation to the virtual camera proportional to the translational movement of the user. The proportion of induced rotation was determined in two different ways (see section 4.1). Moreover, we implemented a time-dependent rotational gain, which constantly rotated the virtual world by 1° per second and thus allowed for a small, yet constant redirection[1]. All gains were shaped by the *Positional overall gain* (see section 4.2). 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

According to the findings of the first experiment, humans are less sensitive to walking on a curve when walking slower, allowing a RDW algorithm to apply higher curvature gains while still unnoticed. This allows us to parametrize the induced curvature gain *dynamically* based on walking velocity, in contrast to previous procedures adjusting curvature on other parameters only. We consider those procedures as *static*, represented by a constant parameter value in our implementation. For our dynamic and static curvature adjustment, we chose a curvature gain which is greater than what was found to be 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. 4.2) 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 [6]. In the condition with dynamic curvature adjustment, curvature c was a function of walking velocity v:

$$c(v) = \begin{cases} 0.2 & : \quad v < 0.75 \\ -0.2v + 0.35 & : \quad 0.75 \leq v < 1.00 \\ -0.04v + 0.09 & : \quad 1.00 \leq v < 1.25 \\ 0.13 & : \quad v \leq 1.25 \end{cases} \tag{1}$$

Thus, curvature was the highest for walking speeds below 0.75 m/s, decreased between 0.75 and 1.25 m/s, and remained constant at 0.13 m^{-1} for higher speeds.

4.2 Gain controller: Position in tracked space

According to the findings of Engel et al. [3], it is disadvantageous to redirect the user into corners of the real world area. Therefore, we attempted to redirect the user to walk on a circle around the centre of the real-world walking area. To achieve this, we created a function providing a shape factor for redirection gains. When returning low values, reflecting no immediate need for redirection, minimal redirection is applied by the different basic redirection methods. For example, the value of induced curvature is reduced, curvature gain thus being similar to the found detection thresholds of Experiment 1.

The first purpose of the function is to watch the global heading (*yaw*) angle of the user and to penalise angles heading towards or away from the centre. The second purpose is to apply higher gains when the user is approaching the walls in order to introduce a greater amount of redirection, potentially leading the user away the walls. Consequently, position gain g is a function of both the user's planar position (x,y) and heading angle α:

$$g_{pos}(x,y,\alpha) = \frac{|sin(\alpha)|}{bound-|x|} + \frac{|cos(\alpha)|}{bound-|y|} - \frac{|cos(\alpha)|-|sin(\alpha)|}{bound} + 1 \tag{2}$$

The variable *bound* is representing the real-world boundaries of the walking area (including a small safety buffer). A graph of the return values for an exemplary heading angle of 45° at the origin is shown in figure 10. In order to avoid extreme gains, the output of the function was limited to 0.5 - 1.5 for the experiment.

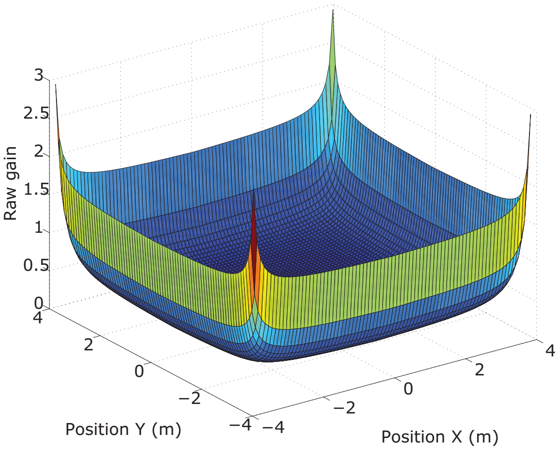


Fig. 10. Position-based gain determination for 45° heading angle for equation (2).

4.3 Reorientation technique

As stated before by Engel et al. [3], 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 trajectories with little head rotation) and/or takes the wrong turns at the wrong time. So there is the need to introduce a ROT as the ultimate means to prevent users from leaving the physical walking area. Based on the findings of Williams et al. [4], we decided to use a ROT that displays a stop sign to the users and *freezes* the virtual world (see figure 11). This ROT ("*freeze-turn*") was chosen due to the higher comfort of turning on the spot compared to walking backwards ("*freeze-backup*") and the better scalability to arbitrary real-world target rotations compared to full 180° rotations ("*2:1 turn*"). 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.

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[1] The value of 3° per second proposed by Razzaque et al. [2] was subjectively too strong during the pilot study and thus reduced.

Fig. 11. Reorientation technique using a stop sign

4.4 Avatar redirection support

A possibly more natural ROT would be to use virtual humans instead of a stop sign: In social interactions, people maintain several *rings* of distance limits in interpersonal space (described by Hall [31], summarized in Llobera et al. [32]). Four rings of interpersonal space are distinguished: public, social, personal and intimate, with interpersonal distances ranging from $\geq$ 7.5 m to $\leq$ 15 cm. This principle has been called *proxemics* [31]. Bailenson et al. [33], Wilcox et al. [34] and Llobera et al. [32] found that this concept of personal space holds true in virtual worlds as well as in real surroundings. For instance, a single avatar which is presented (too) close to a person immersed in VR causes an increase in anxiety as measured by Galvanic Skin Response [34]. This effect is even more pronounced if several avatars are presented at the same time [32]. Therefore, avatars in VEs might serve as a means to influence the user from within the virtual world. An avatar which is perceived as invading personal space might force the user to move in order to establish a more comfortable interpersonal distance, therefore creating an opportunity for redirection.

We created an avatar component for the RDW controller that makes use of two types of avatar redirection (see figure 12). 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. This additional movement, especially head rotation, can potentially be exploited by the underlying RDW algorithms, thus leading to additional redirection. This implementation is only a first and simple attempt at using avatars as distractors / ROT.

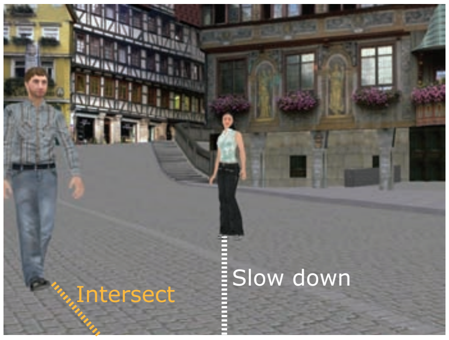

Fig. 12. The two avatar concepts (slowing down and intersecting) which were used for redirection support

5 EXPERIMENT 2: EVALUATION OF DYNAMIC RDW

There were three aims of the second experiment. First, we aimed to test the usefulness of a dynamic gain controller for RDW versus existing state-of-the-art algorithms. Therefore, we used the dynamic gain controller described above which adjusts the curvature gain with respect to the instantaneous walking velocity of the user. Second, we aimed to enable unaided free exploration of a virtual environment. Therefore, we use a new measure of the success of RDW algorithms, namely the distance a person can walk without having to use a ROT. Finally, we aimed to evaluate the usefulness of a first implementation of avatars as a ROT which could potentially reduce the number of unnatural ROT (stop signs) that a person sees during free exploration.

5.1 Method

To measure the effectiveness of the *Dynamic Curvature Gain* controller and the *Avatar* algorithms, we had our participants explore the virtual model of a city while walking around in a real-world experimental area of 8.6 × 8.6 meters. In a between-subject experimental design, we tested the four conditions (factors: Dynamic Controller and Avatars visible).

Each participant walked for one virtual kilometre in the VE per trial. A repetition trial was conducted on the same condition consecutively after a short break. All participants filled out one SSQ each before and after the experiment and an experiment-specific questionnaire.

The experiment was completed by 32 participants (17♀, 15♂, age 19-51, ⌀ 27.26). Three additional participants (each in different experimental conditions) decided to stop the experiment due to motion sickness.

As the main dependent measure, we determined the distances that the participants could walk before reaching the boundaries of the experimental area (indicated by the stop sign). Out of these distances, we also determined the maximum walked distance. In addition, we determined the number of stop sign occurrences, the necessary turning angle to overcome the reorientation phase, the time which was spent for reorientation, the time which the participants could walk freely, the average walking velocity and the

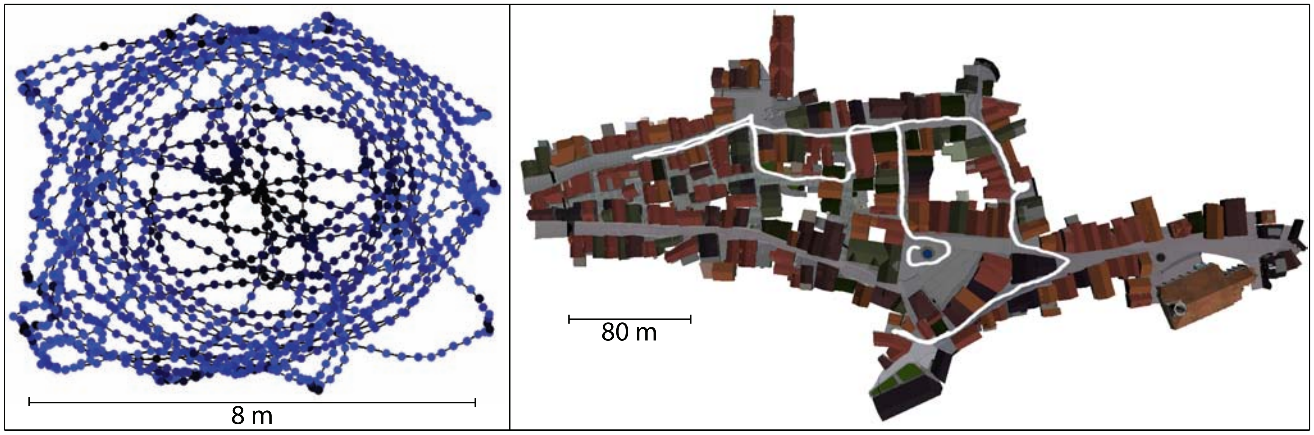

Fig. 13. Illustration of one participant's walked paths in the real world (left) and virtual Tübingen (right). Blue and black indicates higher and lower gains, respectively.

average applied positional and curvature gains. As the obverse of applying more gain is a higher probability of Simulator Sickness, we also evaluated the SSQs.

5.2 Experimental setup

In this experiment, we decided to use a HMD with a larger FOV and a higher resolution than in the first experiment to enhance immersion within the virtual environment (*nVisor SX60* HMD with a resolution of 1280 × 1024 pixels, a refresh rate of 60 Hz and a diagonal FOV of 60°). The duration of the experiment was planned to be 15-20 minutes per block, so the bigger weight (approximately 1 kg) of the HMD was not considered to be a problem. For this experiment, we used the virtual model of Tübingen, Germany [35] which is approximately 500 × 150 m in size. 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. The participants were instructed to walk around in the city freely and to stop as described when seeing the stop sign. Figure 13 shows a top-down view of one participant's walking path in both the tracking hall and *Virtual Tübingen* [35].

When the avatars were visible, 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 between the remaining avatars (see figure 12).

5.3 Results

The results show a high difference in the mean walked distance (see figure 14) between reorientations for conditions with static and dynamic curvature gain. While participants reached the boundaries of the experimental area after approximately 15 meters on average ($SE = 0.49m$) for conditions with static curvature gain, the application of dynamic curvature gain allowed them to walk for approximately 22 meters ($SE = 0.64m$) before reaching these boundaries. We conducted a two-way ANOVA with these distances as dependant variables and found a significant effect for the controller (dynamic and static) factor ($F(1,28) = 82.416, p = 0.001, \eta_p^2 = 0.746$). For the visibility of avatars, the results showed no significant improvement on the mean walked distances between reorientations, $F(1,28) = 0.031, p = 0.861$. We also did not find a significant interaction effect, $F(1,28) = 1.452, p = 0.238$. For the dynamic controller factor, we found a significant effect on maximum distance, $F(1,28) = 30.414, p \leq 0.001, \eta_p^2 = 0.521$, but not for the avatar visibility, $F(1,28) = 0.048, p = 0.829$. We did not find a significant interaction effect, $F(1,28) = 0.634, p =$

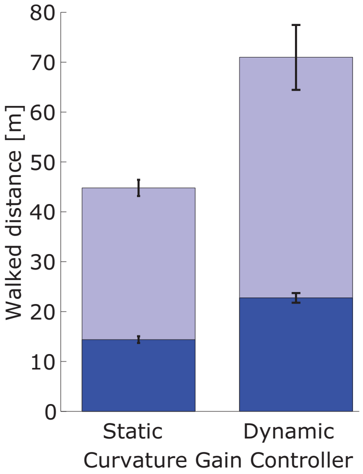

Fig. 14. Free walking distances before the need for a ROT in the two controller conditions. Mean (dark colors) and maximum (light colors) distances are shown; error bars denote one standard error of the mean. Non-significant differences between the avatar conditions are not shown.

0.432.

A two-way ANOVA comparing the SSQ values showed no significant difference neither when using the dynamic gain controller, $F(1,28) = 0.808, p = 0.376$, nor when using the avatar condition, $F(1,28) = 0.651, p = 0.427$. Also, we did not find an interaction effect, $F(1,28) = 2.529, p = 0.123$. The SSQ scores of this experiment are similar to those in Experiment 1 and match those reported in the literature [25], [26], [27].

We analysed the actually applied positional and curvature gain. To better visualize the gain usage, we transformed the applied positional gain g_{pos} into relative gain (cf. Engel et al. [3]) by subtracting it from one: $g_{rel} = 1 - g_{pos}$. We preferred relative gain over absolute gain (as described by Steinicke et al. [1], [15]) for this analysis as it is symmetrical around zero and thus more descriptive to visualize the manipulation of the user's movement without regard of the direction of the manipulation (see figure 15). Relative gain can be considered as the percentage of manipulation. We conducted a two-way ANOVA with applied gains as dependent variable and found a significant effect of the dynamic controller on both positional, $F(1,28) = 18.091, p \leq 0.001, \eta_p^2 = 0.393$, as well as on curvature gain, $F(1,28) = 191.751, p \leq 0.001, \eta_p^2 = 0.873$. We did not find significant effects for the avatar condition ($F(1,28) = 1.184, p = 0.286$ and $F(1,28) = 0.016, p = 0.900$, respectively) nor significant interactions ($F(1,28) = 0.192 p = 0.665$ and $F(1,28) = 0.102, p = 0.752$).
Also, the average walking velocity did not differ over the different conditions (Dynamic controller: $F(1,28) = 4.014, p = 0.055$; Avatars: $F(1,28) \leq 0.001, p = 0.983$; Interaction: $F(1,28) = 0.201, p = 0.658$).

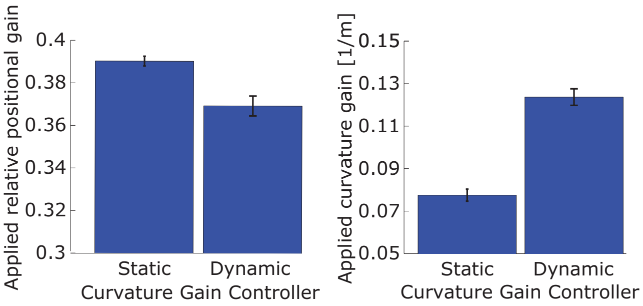

Fig. 15. Absolute value of actually applied relative positional gain (left) and actually applied curvature gain (right); error bars denote one standard error of the mean.

We analysed the actual total time which it took to walk the entire one virtual kilometre (see figure 16). A two-way ANOVA with the total time per trial as dependent variable revealed an effect for the controller, $F(1,28) = 7.420, p = 0.011, \eta_p^2 = 0.209$. While it took our participants on average 19 minutes ($SE = 45s$) to complete one trial in the static gain controller, it took them on average 16 minutes 28 seconds ($SE = 31s$) in the dynamic gain controller. In contrast, we did not find an effect of the avatar condition on total time per block, $F(1,28) \leq 0.001, p = 0.990$, nor a significant interaction, $F(1,28) = 1.345, p = 0.256$.

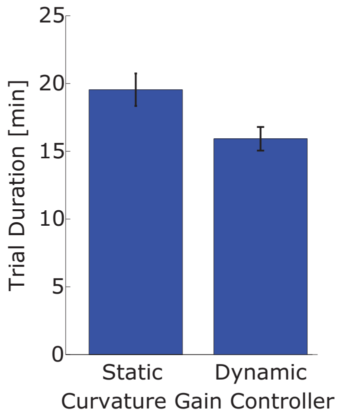

Fig. 16. The average duration it took participants to walk one kilometre in VR. Error bars denote one standard error of the mean.

5.4 Discussion

In this second experiment, we implemented a dynamic gain controller for Redirected Walking which enables participants to independently explore a virtual city and freely choose the direction of travel. We implemented a Reorientation Technique (stop sign) for when the redirection was not sufficient and additionally implemented a concept of avatar redirection as a less intrusive method of redirection. Our motivation was to enable participants to walk unaided and freely in a large scale virtual world using state-of-the-art RDW algorithms, and to extend the state-of-the-art with a velocity-dependent curvature gain controller.

We found a significant improvement on the distance which could be walked without having to be stopped by the stop sign when using our dynamic gain controller as compared to a static gain controller. This did not come at the cost of an increase of SSQ values when using the higher, dynamically adjusted curvature gain. Also, we found a significant lower positional gain for the conditions in which the dynamic controller was used. Due to the fact that this gain shaping factor is derived from the real-world position and orientation of the user, this lower value reflects an overall decreased need for redirection when using the dynamic curvature gain controller. 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 setup. However, further research would need to be conducted to investigate human sensitivity within a rich-cue environment, such as *Virtual Tübingen*.

We matched the gains used for the static and dynamic controller for walking speeds greater than or equal to 1.25 m/s, both values were set to 0.13 m^{-1}. This was based on the expectation that participants would walk on average close to a normal walking speed. Since participants walked substantially slower, the gains used for the static versus dynamic gain controllers differed substantially. This is likely the reason that the mean walked distances are greater for the dynamic than they were for the static gain controller. Additional research needs to be conducted where participants are given a goal directed task, which will likely encourage them to walk closer to a normal walking speed.

The newly created concept of using avatars for redirection did not lead to a significant rise in the walkable distance before needing a ROT. The reason that the implemented avatars may not have decreased the distances between reorientations might originate from the fact that the participants walked relatively slowly ($\varnothing \approx 0.6$ m/s) when they explored the virtual city. We expected participants to walk faster, so this velocity was below the action threshold of the slowing down avatar which was virtually walking in front of the participants. Additionally, the intersecting avatar must not have attracted as much attention as we had hoped. This could have been due to the fact that the slowing down avatar (usually in the centre of the visual field) was always present, and so the intersecting avatar was competing for attention. Further development and research needs to be conducted in order to use avatars as a more natural ROT.

6 CONCLUSIONS

We investigated the perception of curvature in walking and its possible applications in VR. Experiment 1 showed that people are significantly less likely to notice that they walk on a curved path when they walk slower. In Experiment 2, we combined this result with existing *Redirected Walking* techniques and implemented a dynamic curvature gain controller. Curvature gain was made dependent on walking speed, with higher gains applied for lower walking speeds. In addition, the gain also depended on the position in the physical space, as well as on the heading direction. Results showed that participants were able to walk farther with this dynamic gain controller before needing to be reoriented than with a static gain. This did not come at the cost of an increase in simulator sickness. Additional manipulation of walking behavior by the use of avatars did not prove to be successful. In sum, our results show that basic knowledge about self-motion perception can be used to improve free exploration in VR. At the same time, they show how a practical problem in VR can lead to interesting theoretical questions in basic perception science.

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