Rethinking Redirected Walking: On the Use of Curvature Gains Beyond Perceptual Limitations and Revisiting Bending Gains

Michael Rietzler* Jan Gugenheimer* Teresa Hirzle*
Martin Deubzer* Eike Langbehn† Enrico Rukzio*
*Institute of Media Informatics Ulm University
†Human-Computer Interaction Group Hamburg University

Abstract

Redirected walking (RDW) allows virtual reality (VR) users to walk infinitely while staying inside a finite physical space through subtle shifts (gains) of the scene to redirect them back inside the volume. All prior approaches measure the feasibility of RDW techniques based on if the user perceives the manipulation, leading to rather small applicable gains. However, we treat RDW as an interaction technique and therefore use visually perceivable gains instead of using the perception of manipulation. We revisited prior experiments with focus on applied gains and additionally tested higher gains on the basis of applicability in a user study. We found that users accept curvature gains up to $20°/m$, which reduces the necessary physical volume down to approximately 6x6m for virtually walking infinitely straight ahead. Our findings strife to rethink the usage of redirection from being unperceived to being applicable and natural.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies

1 Introduction

Technologies like virtual reality (VR) and augmented reality (AR) are more and more becoming a topic of interest for the consumer market. One open problem is the navigation in such virtual environments. Real walking is the most natural and simple way of moving around in a virtual environment [34], but it is also the most difficult one to realize since it requires the real world providing the same space as the virtual one. One idea to overcome this limitation is redirected walking (RDW) [27]. RDW is a technique where the path walked in the real world slightly differs from the virtual one by manipulating the user's orientation, or other features during walking. As long as this manipulation is designed subtle enough, users do not even recognize the manipulation. According to Steinicke et al. [31] the manipulation may not exceed a gain of $2.6°/m$ or according to Grechkin et al. [12] $4.9°/m$ to prevent its detection. When applying such gains it is possible to virtually walk straight forward while walking on a circle in the real world without perceiving the shifting. Though, the diameter of the walked circle would be around 44 m [31] (or 22m [12]), which is far too much for most applications. It was also suggested to enhance the concept of RDW by guiding users to walk on curved paths [19]. The virtual curve adds to the curve induced by the gain and therefore results in less required space. Forcing users to walk curved paths reduces the desired tracking space, but requires a special design of the virtual environment and therefore strongly limits the application.

The current state-of-the-art of navigation in a roomscale VR is the *point and teleport technique* (eg. [8]). Teleporting solves different problems of VR navigation. On one hand, it solves the problem of limited space, since real walking is only used for short distances, while longer distances are traveled by using the teleport metaphor. Some other techniques, like indirectly controlling movements by a controller, cause motion sickness, a problem assumed to be caused by the conflicting visual and vestibular information during accelerations [20]. Since there is no acceleration when traveling between two points without animating the motion, motion sickness does not occur during teleporting. Nevertheless, there are also some drawbacks of teleportation. It might break the sense of feeling present in a virtual environment, but primarily, teleportation decreases the spatial orientation and the knowledge about the surrounding [1, 6, 10, 29].

Similar to metaphors like teleportation, we assume, that redirected walking may be designed beyond the perceptual limitations and could be accepted as navigation technique even if the manipulation is detected. We therefore conducted an experiment including higher gains then the already proposed ones. In contrast to prior works, we did not target our experiment to get insights on perceptual thresholds, but on participants preferences. We asked participants how natural the walking was and if the gain would be applicable to realize movement in VR. Since a stronger manipulation of the rotation could also induce motion sickness, we also asked participants to state if they suffered related symptoms.

To allow a fair comparison of prior works, as well as to compare detection thresholds to our results we propose the use of a unified metric being $°/m$ for curvature gains. Using this metric, we rerun the experiment of [19] and propose corrected perceptual thresholds that are much lower to the prior reported. Our proposed applicability metric showed that it is possible to apply twice the detection threshold without influencing the perceived naturalness or increasing symptoms of motion sickness. Participants even accepted four times the detection threshold of around $5.2\ °/m$ to be applicable. This way, the required space for infinitely walking a straight line can be reduced to 6x6m.

Our main contributions are:

- The approach of treating RDW as an interaction technique and evaluating it based on applicability metrics and not on the basis of perception.
- Proposing a unified metric to represent curvature gains in RDW and rerun a prior experiment showing how to apply our new metric.
- Findings from a user study showing that by treating RDW as an interaction technique $20°/m$ was acceptable for users, while they detected the manipulation at a gain of $5.2°/m$.

2 Related Work

2.1 Navigation

Navigation in VR can be separated into the cognitive and physical components way-finding and (active or passive) travel [5]. While way-finding is the spatio-cognitive process of finding a way from one location to another, travel denotes the actual movement within the virtual environment. Travel can be carried out passive, e. g. by

*firstname.lastname@uni-ulm.de
†langbehn@informatik.uni-hamburg.de

using a joystick, or active, i. e., the user moves physically, which is often denoted as *locomotion*. While real walking is considered to be the most natural way of moving through a virtual world [34], other locomotion techniques were introduced due to the spatial limitations of the real world [32]. These include a wide range of approaches like omni-directional treadmills (e.g., [3,4]) or even robot controlled moving floor parts ([15]). Furthermore, walking-in-place techniques (e.g., [17, 23]) and redirected walking [27] were investigated.

2.2 Redirected Walking

The idea of RDW is to compensate the limited tracking space by manipulating the user's orientation, position or other features. The manipulation of the user's orientation during walking is called curvature gains, which let's the user walk in a circle instead of straight forward as she does seemingly in the virtual world [27]. When the discrepancy between the virtual travel path and the actual travel path in the real world is small enough, this redirection is not detected by the user [31]. Beside these curvature gains, it was also suggested to apply gains on the velocity during walking (translation gains) [14], or to apply rotation gains while standing on the spot and turning around [16]. Suma et al. [33] introduced a taxonomy of different redirection and reorientation methods ranging from discrete to continuous, and subtle to overt.

Because the physical tracking spaces are usually not large enough to enable unlimited undetected redirected walking, different strategies are needed to keep the user inside the boundaries. Originally, Razzaque presented three different algorithms for that: Steer-to-center, steer-to-orbit, and steer-to-multiple-targets [26]. If the user still collides with the boundaries of the tracking space, a reorientation phase is started in which the user is turned around towards the tracking space. To make these reorientation phases less obvious, Peck et al. introduced distractors [25]. To avoid interruptions like this, Hodgson et al. [13] presented an algorithm for very large spaces, i. e., 45m× 45m. Another solution, which limits the required space was suggested by Langbehn et al. [18]. They propose to force the user to walk on already curved paths. In addition, they claim various detection thresholds to realize such a setup without being perceived.

2.3 Curvature Gain Detection Thresholds

When applying curvature gains, Razzaque [26] found that a manipulation of $1°/s$ is the detection threshold under worst-case conditions. In other experiments, the strength of gains is applied depending on the walked distance. For example, it was suggested, that a redirection should not go beyond $2.6°/m$, since participants perceived higher gains and therefore noticed the manipulation [31]. Such a gain would require a circle with a diameter of 44m to infinitely walk virtually straight forward. Grechkin et al. [12] regarded the influence of using translation gains while applying curvature gains. They found that the detection thresholds of curvature gains were not significantly influenced by translation gains. According to their results users are less sensitive to curvature gains than reported by Steinicke et al. and state a required radius of around 12m.

While detection thresholds of curvature gains are not significantly influenced by translation gains, it has been shown that other factors influence the detection thresholds. This is for example the presence of cognitive tasks [9], the velocity of walking [22], or the presence of passive haptic feedback [21]. The visual density of the virtual environment seems to have no influence on the detection of rotation gains [24].

Another kind of curvature gains were proposed as *bending gains* [19]. These gains are defined as the relation between real and virtual radius. As we show in the following, they can be directly converted to curvature gains and are unsuitable to measure perceptual thresholds.

3 Conversion of Other Notations

Detection thresholds are often provided in various and even incomparable ways. In the following we show that stating the radius, although being a proper way of communicating the required space, is no adequate way of comparing gains. We therefore suggest to use a uniform way of describing gains, provide formulas to convert priorly reported gains and compare them by converting them into the proposed metric.

The most prominent factor that a user perceives during RDW is to be rotated by a certain amount of degrees after walking a certain distance. We therefore argue to use the notation angle per walked meter ($°/m$). This unit can be interpreted as: *after a user walked a distance of 1m, he will be rotated by x degrees*. A similar metric was already used in the experiment by Steinicke et al.: They calculated the curvature gains g_C based on the scene rotation after 5m walking distance [31].

A lot of literature in the field of detection thresholds for RDW uses radii to describe curvature gains. But radii do not scale linearly to the perceived manipulation (see figure 1 b). While for example the gains proposed by Grechkin ($4.9\ °/m$) result in a radius of around 12m, the ones provided by Steinicke et al. being little lower ($2.6\ °/m$) result in a radius of 22m – a difference of 10m regarding the radius (while the degrees per meters differ by 2.3). Adding the respective difference of $2.3°/m$ to Grechkin et al.'s $4.9\ °/m$ leads to a gain of $7.2°/m$ and to a radius of around 8m – a difference of only around 4 m with the same difference of $2.3°/m$. Radii do not increase or decrease in a linear way with the perceived manipulation and are therefore no adequate metric to compare gains. We therefore argue, that the use of radii to state the required physical space using a redirected walking gain is though useful to communicating the effects of a gain, are no proper way for comparing gains. We encourage further reports on curvature gains to state the radii as well as gains in the unit $°/m$ to allow a fair comparison with prior works. Figure 1 b) shows the relation of radii to the perceived gain in $°/m$.

We are aware that using the rotation after walking 1 m as unit might not be the perfect solution, too, since we already know that e.g., walking velocity or acceleration also influence the perception of RDW gains [22]. The unit $°/m$ does not consider such temporal effects. However, we argue that they are a more precise way to compare the already proposed detection thresholds, since they increase linearly with the perceived manipulation. Additionally, we can assume that participants walk more or less in a same speed and can also be instructed to do so.

We therefore propose formulas to convert prior gains into the proposed unit. A simple radius can be converted into *angle per meter* by considering the perimeter of the respective radius (which is $P = 2\pi r$). Since a circle comprises a full 360° rotation, the rotation per meter is given by $\frac{360°}{P}$. This principle is illustrated in figure 1 a).

The notation used e.g., by Steinicke et al. [31] which describes the gains as degrees per overall walked distance can be easily converted by dividing the gain by the walked distance.

Grechkin et al. [12] draw their psychometric function in the unit m^{-1}, which is interpreted as how much a user is redirected (in m) after a walked distance of 1m. To translate this unit into the proposed notation, one has to imagine a right triangle with the adjacent side being the walked distance and the opposite side being the gain (g) which is walked sideways. Since the walked distance and therefore the adjacent side is always 1 (in their notation), the gain can be calculated by $\arctan g$.

The *bending gains* proposed by Langbehn et al., are defined as a scale between virtual and real radius. They can be converted by translating both radii to $°/m$ (as already described) and then subtracting both values. This can be interpreted as the difference of the curvature between real and virtual curve in the unit angle per meter.

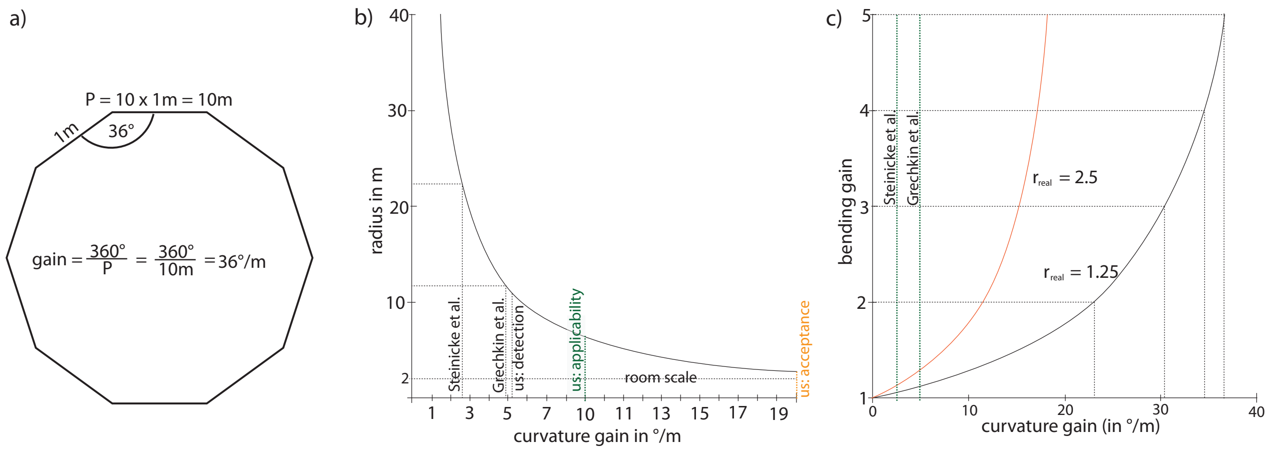

Figure 1: a) The principle of converting radii to degree per meter can be simplified as follows: A circle can be split in an endless amount of segments. When splitting the circle into 10 segments with the length of 1m, a user will be rotated after this meter by 36°.
b) Radii do not scale linearly to the perceived gains. The illustration also shows how high gains would be needed to reach a room scale radius.
c) The bending gains proposed by Langbehn et al. do not scale linearly with the perceived manipulation. They also depend on the underlying real radius (compare orange and black curve). Note: the drawn bending gains were used in their evaluation. Even the first tested ones are much higher then the prior reported detection thresholds.

4 Experiment 1: Revisiting Curvature and Bending Gains: Validation and Comparison

When comparing the different detection thresholds in a unified metric, we found the proposed values to be exceedingly differing. Steinicke et al. [31] propose 2.6°$/m$), Grechkin et al. [12] 4.9°$/m$) and Langbehn et al. [19] 15.4°$/m$ or even 31.7°$/m$, depending on the condition. We therefore decided to not only run the experiment testing the applicability, but also revisiting prior experiments to get a valid ground truth for comparing applicability with detection. With revisiting we do not mean reproducing the exact study setup and experiment but rather tried to reproduce the stated results, which should be independent to minor variations. These differences are discussed in the *Method* section.

4.1 Setup

The study took place in a 10x8m laboratory room. As HMD we used the Oculus Rift and realized the tracking via the respective sensors. We used 3 Sensors that were placed in a triangle around the tracking space. This way we span a tracking space of around 5x5 meters.

4.2 Method

For the reassessment of the results of Langbehn et al. as well as the results of prior gains for straight walking, we stick to the most common method: a two-alternative forced-choice (2AFC) task. In the following we discuss the differences between Langbehn et al.'s and our experiment design.

Number of repetitions: The validity and expressiveness of such a test is strongly depending on the number of repetitions per participant. We therefore decided to use 10 repetitions equally distributed in left and right curves in contrast to Langbehn et al. who repeated two times per gain and direction.

Tested gains: We decided to test the gains 2, 4, 8 and 12 °$/m$. We aimed at testing the same gains for walking a straight line and a curve to allow a comparison between both conditions. This is why we substituted bending gains by the given gain and the instruction and visually guiding to walk a virtual curve with 12.5m radius (4.6 °$/m$) or 5m radius (11.5 °$/m$).

Question: Most important, was to choose a question which should be about the detection of manipulation instead of the direction of manipulation (as it was done in e.g. [19]). Though it is possible to ask whether a participant could perceive a manipulation, such yes/no tasks can be highly biased, since there is no validation. A participant may really detect the manipulation or just claim to perceive it. We therefore decided to let the participants walk there and back again, while only one way was manipulated. We then asked the participants to state whether they were manipulated on the way there or back.

The experiment was conducted as within-subjects design with two independent variables (gain and virtual curve).

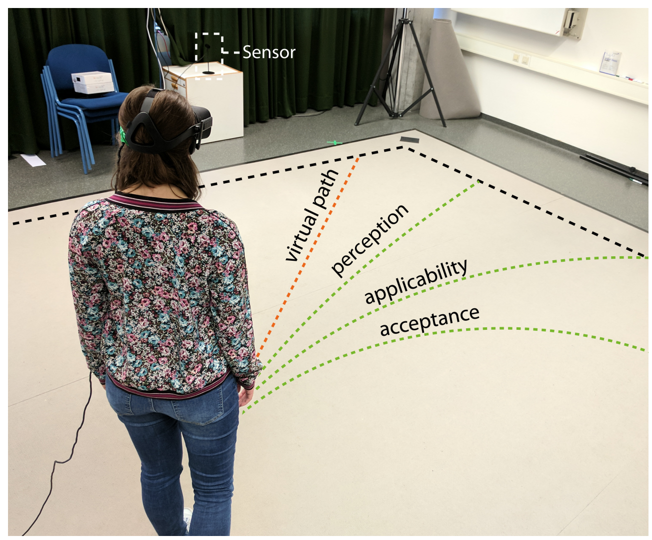

Figure 2: The laboratory including the tracking space. Illustrated is the virtual path (without curve), as well as the detection threshold of around 5°$/m$, the applicability gain of 10°$/m$ and the acceptance gain of 20°$/m$

4.3 Procedure

We first informed the participants about the target of the evaluation, being navigation in virtual environments. We then asked the participants to sign a declaration of consent and to fill in a demographic questionnaire.

For each test, the participants walked 4m there and 4m back again. When the target was reached, the participants answered the described question while remaining in the virtual environment. The participants were then visually guided to the next start position without any gains. When the participant was ready, the next condition started. This sequence was repeated until the end of the study. The order of the 120 trials (4 gains x 3 curves x 10 repetitions) was randomized. The participants could break or abort the study at any time. The whole study, including the 2AFC and applicability task, lasted between 1,5 and 2 hours, depending on the participants velocity of walking and number of breaks.

4.4 Participants

We recruited 16 participants (most of all students and employees of our university). The participants (5 female) were aged between 20 and 30 (mean: 26). There were four novice VR users who never experienced VR before as well as two very experienced users with more then 50 hours of experience (mean experience with VR: 15 hours). Each participant was compensated with 10 €.

4.5 Results

The results of the 2AFC task are illustrated in figure 3. The virtual curvature had only little effect on the detection of being manipulated. Our results of walking a straight line, with a detection threshold of around $5.2°/m$ confirm the results of Grechkin et al.'s $4.9°/m$. Though our results cannot be directly compared to Langehn et al.'s results due to the difference of the tested gains and the different 2AFC task, our results obviously differ. While their results for detecting the direction of manipulation suggest detection thresholds of up to $30°/m$, our results show that the detection of manipulation is quite similar to walking a straight line ($5.5°/m$ or $5.7°/m$). We also compared the probability of detection of the two critical measuring points being 4 and $8°/m$ (the ones below and above the detection threshold) between the three tested virtual curvatures. A Friedmann test for dependant variables showed no significant difference when comparing probability of detecting a gain of $4°/m$ (*p=.68; F=.76; r=.11*). Comparing the probability detecting a gain of $8°/m$ proved to be not significant as well (*p=.88; F=.26; r=.04*).

4.6 Discussion

We argue that the detection thresholds are close to independent from but slightly increasing with the virtual curve being all around 5 or $6°/m$. Our results are inline with prior results, like those of Grechkin et al. [12]. Though, as can be seen in figure 3, there were large variances considering the detection of the different participants. This could either be due to perceptual differences between the participants or it could be originated in random effects caused by too less repetitions.

4.7 Revisiting Bending Gains

Our results stand in great contrast to the ones proposed by Langbehn et al. [19]. While they even stated detection thresholds of more than $30°/m$ when virtually walking a sharper curve (which is around 6 times higher then the yet reported detection thresholds for walking a straight line), we found the detection threshold to be close to independent from the virtual curve (still around $5°/m$). In the following we explain how this enormous difference arose.

Bending gains were defined as a factor scaling the real radius to the virtual one. As we already described, bending gains can directly be converted to the already known curvature gains. But we further argue, that the proposed *bending gains* should not be used for psychometric experiments. Depending on the relation of two radii which do not increase in linear way to the perceived manipulation (see figure 1 b), the resulting curvature gain strongly depends on the real radius on which the *bending gain* is applied. Therefore the same *bending gain* will result in different curvature gains when applied to different real radii. The *bending gain* of 2, for example, applied to the real radius of 1m results in a curvature gain of around $29°/m$, while applied to a real radius of 2m leads to a curvature gain of only around $14°/m$. A function that illustrates the correlation between bending and curvature gains is shown in figure 1 c).

Comparing the detection thresholds of Langbehn et al. with the ones presented in prior works, the proposed detection thresholds are dramatically higher. Even while walking on a 12.5m radius in reality, which is close to walking straight forward, the proposed detection threshold of around $15.4°/m$ is three or even six times higher then the priorly proposed ones of 2.6 [31] or $4.9°/m$ [12].

A first reason for these higher gains might be the used two-alternative forced-choice (2AFC) task. The question that was asked was *"At which side from the virtual path did you walk physically in the real world?"* and the participants had the options to answer *left* or *right*. Grechkin et al. [12] already pointed out that this method is not necessarily the optimal way to estimate detection thresholds. Though this might still work for detection thresholds of straight virtual paths, it is very hard to estimate the direction of manipulation when walking a curve while being re-orientated by gains. Further, the ability of estimating the direction is strongly influenced by disorientation, which increases with higher gains. Therefore, higher gains might even lead to lower probabilities of detection. This is due to the discordance of the direction of gain and virtual curve. Since the authors asked explicitly for the direction of manipulation, their results cannot be interpreted as detection threshold for being aware of a manipulation.

As already described, radii do not scale in a linear way with the perceived manipulation. This leads to another problem of the proposed *bending gains* when creating psychometric functions. When, for example, using the suggested 1.25m radius for the circle walked in the real world which is stretched by the factor 2, the resulting virtual radius is 2.5m. The proposed gains of 1, 2, 3, 4 and 5 therefore result in the gains of 0, 23, 30, 34 and 37 $°/m$. This example is also illustrated in figure 1 c). While the difference between the first two gains is $23°/m$, the difference between the last two is only $3°/m$. Assuming a linear distribution of these gains in a psychometric function leads to errors when calculating the detection threshold. In addition, there is a risk of testing gains, which are unrelated to the level of detection. In the case of the presented study, even the lowest tested gain of $23°/m$ was already close to five times the priorly stated detection thresholds.

The nonlinear distribution of the proposed gains though leads to another problem. The authors also assumed their gains of 2, 3, 4 and 5 to behave symmetric to the gains $\frac{1}{2}, \frac{1}{3}, \frac{1}{4}$ and $\frac{1}{5}$, though they are not. Comparing their proposed real world radii of 6.25m and 1.25m which were modified using their proposed thresholds, they assume the following gains to be equal: 23 to $9°/m$, 31 to $18°/m$, 34 to $28°/m$ and 37 to $37°/m$. The proposed psychometric function, drawn in a symmetric way and assuming the described gains to be similar, can therefore not be considered as valid.

Furthermore, the validity of a 2AFC task increases with the number of repetitions per condition. The underlying assumption of such a test is that if a participant is unaware of a stimulus, but has to decide between two options, he will choose each of them just as often. When the stimulus gets stronger, the participant will tend to one of the answers. If for example a coin is flipped 100 times, head and tail will be most likely be equally distributed. The probability of head and tails are therefore both .5. If only flipping four times, the risk of random probabilities (e.g., three or even four times head) is quite high. The second problem using too view repetitions is the resolution of the sample space. When repeating the experiment four times the resolution of probability is in .25 steps. A participant can either give one of the possible answers no single time ($p = \frac{0}{4} = 0$), one time ($p = \frac{1}{4} = .25$), two times ($p = \frac{2}{4} = .5$), three times ($p = \frac{3}{4} = .75$) or four times ($p = \frac{4}{4} = 1$). When aiming at measuring the threshold of detection as accurate as possible, the resolution has to be higher. Such an experiment therefore requires more then four iterations to consider the results as significant.

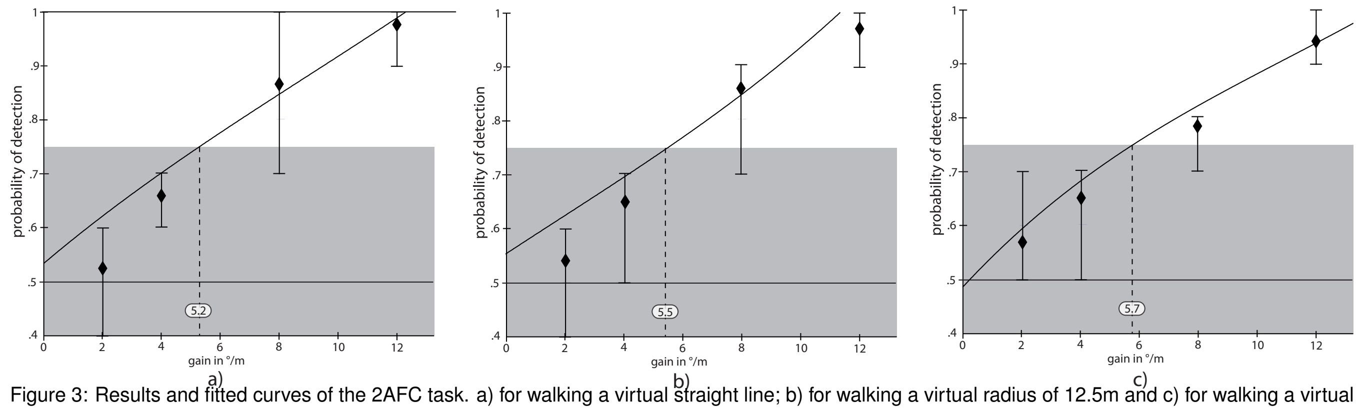

Figure 3: Results and fitted curves of the 2AFC task. a) for walking a virtual straight line; b) for walking a virtual radius of 12.5m and c) for walking a virtual radius of 5m.

Overall, we argue that the results of Langbehn et al. rather measure the estimation of the direction of the manipulation and not the overall detection of a manipulation. Since participants had to walk a virtual and physical curve this turned out to be quite difficult and participants already reported symptoms such as nausea and disorientation without being able to tell the direction of the manipulation. Further, we showed that the use of the proposed *bending gains* are unsuitable for the use in psychometric functions when assuming the *bending gain* to be increasing linearly with the perceived manipulation.

5 Towards the Applicability of Curvature Gains

Since our goal was to treat RDW more as an interaction technique (e.g., teleport) rather than designing it to be unperceivable, we looked into fields beyond RDW using different forms of evaluation metrics.

The following are experiments focusing on the quality of movement strategies. These experiments e.g., measured speed (e.g. [2, 7]), accuracy (e.g. [7]) and asked for spatial awareness (e.g. [7]), ease of learning/simplicity/cognitive demand (e.g. [7, 9, 34]), ease of use (e.g. [7]), information gathering during navigation (e.g. [7]), naturalness (e.g. [34]), simulator sickness (e.g. [2, 28]) or presence (e.g. [2, 7, 28, 30]).

These metrics were used to compare the quality of walking techniques such as walking in place or controller input. There are no results on comparing redirected walking gains beyond the ability to detect the manipulation. Since our goal is to find how strong a user may be manipulated, before a gain is no longer subjectively perceived as applicable.

We therefore build a set of items which we refer to be contributing towards the applicability based on these prior experiments. We deliberately did not include measures like accuracy or speed, since we do not see them contributing to applicability.

Our first applicability item is based on the main motivation for redirected walking: the naturalness compared to other navigation techniques. If the walking is no longer regarded as natural, the main advantage compared to other navigation techniques is no longer complied.

Applying too high gains can disturb our sense of orientation and lead to symptoms of nausea. We therefore used disorientation and nausea as second item. Nausea, disorientation but also the enforcement of walking curves can decrease the comfort of locomotion. Though we assume that comfort will most likely be highly negatively correlated with the symptoms of nausea and disorientation, we used this item as well. The last item is the most obvious one and targets towards the applicability of gains itself. Considering the applicability, the practicability of gains is highly dependant on users' willingness to have such a gain inside a VR application.

6 Experiment 2: Applicabililty Study

Since both, the 2AFC and applicability study were part of the same session, participants and setup were the same as for the first experiment. The 2AFC task was always done before the applicability study.

6.1 Method

Since our aim was to get insights on how far the visual manipulation could go before the movement is no longer pleasant or becomes unnatural, we used seven point Likert scales that were presented directly after the participant reached the target without taking off the VR headset. Since we did not measure the detection thresholds, we did not need to repeat the measurements. Though we tested each condition four times, since we aimed at getting insights on potential customization effects.

We used the applicability items as described earlier. The participants were asked after each condition how much they agree to the following statements: *Walking like this through a virtual world is natural.*, *Walking this way through a virtual world is pleasant.*, *I could imagine using this walking technique to move inside virtual worlds*. The participants should answer on a scale from *1: totally disagree* to *7: totally agree*. In addition, we used a single item to measure potential symptoms of motion sickness by asking *How strong was the feeling of nausea or disorientation during walking?* on a scale from *1: non-existing* to *7: I wanted to abort the test*. Though we already included the item of acceptance as 7-point item, we decided to additionally force the users to either accept or reject a certain gain using the same question (*I could imagine using this walking technique to move inside virtual worlds*) but only with the options *yes* or *no*.

We used the same virtual curves with the radii of r = ∞ (straight line), r = 12.5m and r = 5m, but different gains for this experiment. As ground truth we tested walking without gain ($0°/m$). In addition, we tested a gain around twice the detection threshold ($10°/m$) as well as two very high gains of $20°/m$ and $30\,°/m$.

In addition to the quantitative measures we also asked the participants to provide feedback in textual form.

6.2 Procedure

For each condition, the participants first walked to a visually provided start point and walked the way to the target position. When the target was reached, the participants answered the questions while remaining inside the virtual world (as suggested by [11] to mitigate effects of interruption) by using the Oculus touch controller. After all questions were answered, the participants were guided to the next start position and the next condition was presented. The next task started as soon as the participant reported to have no symptoms of motion sickness. The experiment used a within-subject design with the independent variables being the virtual curve and the applied gain, as it was also done in the 2AFC task. Since we tested three virtual curves and 4 gains and repeated each condition four times, the participants had to walk 48 times (3 curves x 4 gains x 4 iterations).

After finishing all tasks, the participants were asked to fill in a final questionnaire which included textual feedback.

6.3 Results

Boxplots of our applicability items are shown in figure 4. While the median rating of the gains remained positive until $20°/m$, we found a strong decrease of all scores when applying a gain of $30°/m$. These results are mirrored in the rating of nausea and disorientation, which strongly increased for the $30°/m$ condition.

We first regarded the influence of the virtual curves on each score using separate Friedmann tests for dependant variables. Non of the ratings differed significantly, nor showed any noteworthy effect sizes. We therefore argue that the applicability scores, as well as the priorly stated detection thresholds, are not influenced by walking a virtual curve.

For the following analysis we therefore ignore the variable of the virtual curve's radius, since they did not influence the ratings. We therefore only compare the ratings considering the different tested gains.

We compared the sickness scores of the gains (0, 10, 20 and $30°/m$) using Friedman's variance analysis for dependent variables. Since we found a highly significant difference (p=.00), we performed pairwise comparisons using Wilcoxon's signed rank test and adjusted the significance values using the Bonferroni correction. We started with the comparison of nausea and disorientation scores. While the gain of $10°/m$ did not significantly increase the scores (p=.79), $20°/m$ (p<.01) and $30°/m$ (p<.01) did significantly increase the scores.

Regarding the ratings of naturalness, we also found significant differences between the ground truth without manipulation and $20°/m$ (p<.01) and $30°/m$ (p<.01), while $10°/m$ did not show any significant effect.

The same trend is observed regarding the item whether a gain is still pleasant. While $10°/m$ did not differ significantly, $20°/m$ (p<.01) and $30°/m$ (p<.01) significantly decreased the respective ratings.

The rating whether a gain is applicable also did not vary significantly between 0 and $10°/m$, while $20°/m$ (p<.01) and $30°/m$ (p<.01) were significantly less applicable.

Customization: We split the yes/no item about the applicability of gains in two parts (the first two iterations and the last two ones). Since the participants were forced to either answer with yes (1) or no (0), the middle of two trials can either be 1, 0.5 or 0. We interpret the value of 1 to be a certain yes, the value of 0.5 as being undecided and 0 as a certain no. Since the ratings did not differ between the virtual curves, we ignored this parameter in this part of the evaluation. The results are shown in figure 5.

The results mirror the tendencies of the 7-point scales, but show more clearly that the $20°/m$ gain is still applicable. Comparing the first iteration with the second one shows a slight tendency of customization. The participants tended to accept higher gains more likely in the second iteration. Since we only tested four times, we assume that the acceptance could even increase with more trials. While only 9% (or 12% in the first iteration) of the participants did not accept a gain of $20°/m$, 70% (or 50%) fully accepted the gain. $30°/m$ was though obviously seen as not applicable. Only 6% accepted this gain, while 88% stated a clear *no*.

7 Discussion

Our results indicate that users accept gains, even far beyond the level of detection. While our results, as well as prior results, state detection thresholds (though slightly varying) of around $5°/m$, all of our participants accepted twice this gain. The applicability ratings proved that the ratings were not influenced by applying a gain of $10°/m$. We argue that higher gains (up to $20°/m$) can be applied, since they are still perceived as applicable, though they significantly increased nausea and disorientation and decreased the other applicability scores. So even increasing the gains to four times the detection threshold was accepted by 70% of the participants, while only 9% did absolutely deny their applicability.

The presented results are in strong contrast to the results priorly stated by Langbehn et al., who suggest that gains of up to around $32°/m$ are not perceived by users. Our results indicate that such high gains are far beyond being detected and even inapplicable and lead to a strong increase of nausea and disorientation. The other gains suggested by Langbehn et al. are though being far beyond the detection threshold, still around or below our applicability scores. Though we dissent with their detection thresholds, which were not based on measuring the perception of manipulation, we could prove their provided application scenarios. All, except one, of the used gains can be used from the perspective of applicability, though being obviously detected as manipulation.

7.1 Limitations

Though our participants accepted gains of up to $20°/m$, we argue that this gain should not be used constantly. We only tested small sequences of walking and no longer application. In addition, the acceptance ratings have to be regarded with considering other tested scores. They all show, that such high gains are on the edge of being unnatural or unpleasant. In addition, we could observe an increase of disorientation. The $10°/m$, which are still twice the detection threshold, though did not show any significant difference to the ground truth without any gains.

8 Implications

Our results show that gains can be applied far beyond the limitations of detection. Applying twice (or even around 4 times – depending on the source) the detection threshold as gain did not even show any influence regarding the perception of naturalness, comfort, applicability or nausea and disorientation. Applying higher gains like $20°/m$, which is 4 times (our result and [12]) or even 8 times [31] the detection threshold, significantly reduced the applicability scores and increased nausea and disorientation, but were though still perceived as applicable. We therefore argue that redirected walking should not only be considered by measuring detection thresholds, but by considering other ratings which are related to the applicability of gains. We suggest to run similar experiments on other gains, such as translation gains, to allow an even higher compression of the virtual space.

Our results, however, should not be interpreted as hard thresholds. We found that a gain of $10°/m$ can be applied without influencing the respective scores. Though we did not aim at finding an exact point where the scores will be influenced stronger. Therefore gains of $15°/m$ could still be as usable as $10°/m$.

While our detection thresholds of walking a straight line support the results of prior experiments, our results disagree with the results proposed by Langbehn et al. [19]. As we already described, this is due to the unsuitable use of *bending gains* for measuring detection thresholds and due to the different design of the 2AFC experiment (measuring detection of the direction of manipulation instead of the manipulation itself). The suggested use of gains up to $30°/m$ without being detected is even beyond the limit of our proposed applicability metric. We could not find that the virtual curvature does significantly influence detection nor our proposed applicability metric. Therefore, we argue against using bending gains over curvature gains.

We want to emphasize, that we could validate their proposed application of redirected walking in room-scale dimensions based on applicability metrics. Our proposed limit of applicability (being

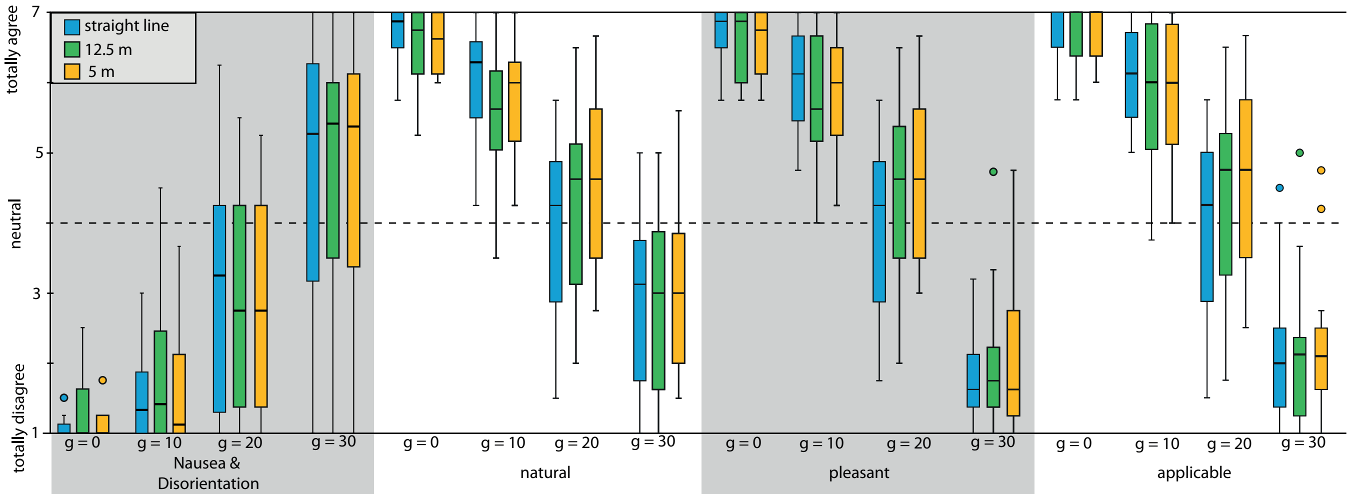

Figure 4: Boxplots of the used applicability items. All gains (g) are provided in the unit $^\circ/m$.

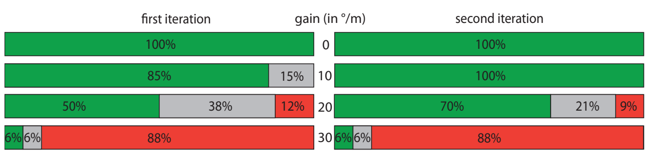

Figure 5: The percentage distribution of accepting the gains (green: yes, gray: undecided and red: no).

around $20^\circ/m$) still requires a space of around 6x6m to infinitely walk a straight virtual line. Forcing the user to walk curved paths can reduce the required space, since the angle of the virtual curve adds to the applied gain. The proposed room-scale application can therefore be realized not under the assumption of letting a user being unaware of the manipulation, but by having the user accept the manipulation. Only one of the proposed gains (which was around $32^\circ/m$) was even too high to be accepted by the participants and should be adjusted accordingly.

9 Conclusion

In this paper we propose a new metric for stating the quality of redirected walking (RDW) gains. We propose several items, based on related work, which we consider to be contributing to the applicability of gains. While prior works focused on designing such gains as subtle, to be not perceived by the user, we found that much higher gains can be applied before reducing the perceived naturalness or applicability, and without increasing nausea or disorientation.

Further, we show that the *bending gains* proposed by Langbehn et al. [19] are unsuitable for psychometric experiments and should be converted to curvature gains. For this we revisited their experiments and found that the proposed detection thresholds are far beyond the actual detection of manipulation. Yet, we could confirm their application to realize RDW in a roomscale setup of 4x4m, though not under the assumption of not detecting the manipulation, but under consideration of our proposed applicability metrics.

We argue that applying applicability metrics is a promising approach to reduce the required real world space, and that similar experiments should be conducted to get insights of the applicability of other RDW gains.

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