

The Influence of Full-Body Representation on Translation and Curvature Gain

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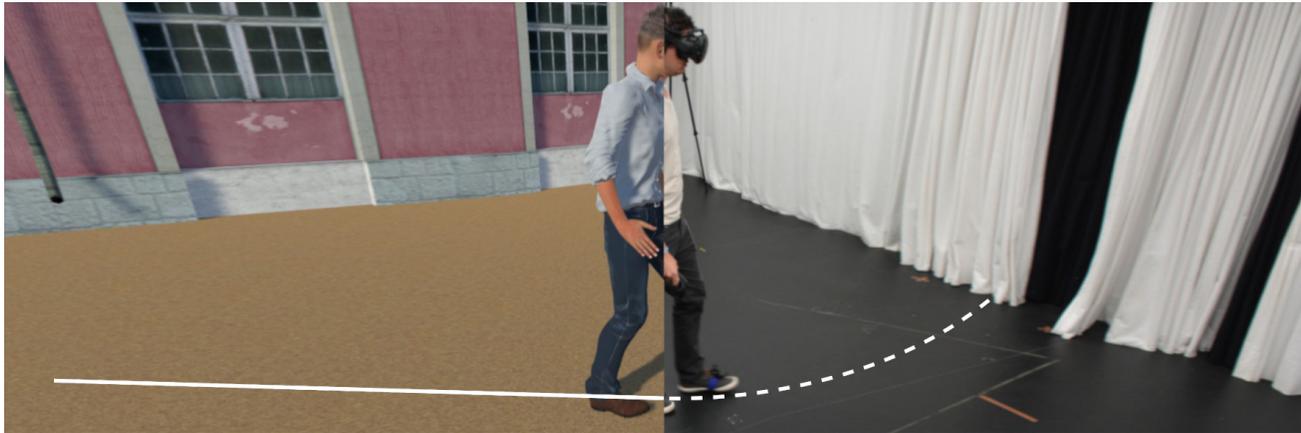


Figure 1: A virtual avatar walking straight, while the real-world path is curved.

ABSTRACT

Redirected Walking (RDW) techniques allow users to navigate immersive virtual environments much larger than the available tracking space by natural walking. Whereas several approaches exist, numerous RDW techniques operate by applying gains of different types to the user's viewport. These gains must remain undetected by the user in order for a RDW technique to support plausible navigation within a virtual environment. The present paper explores the relationship between detection thresholds of redirection gains and the presence of a self-avatar within the virtual environment. In four psychophysical experiments we estimated the thresholds of curvature and translation gain with and without a virtual body. The goal was to evaluate whether a full-body representation has an impact on the detection thresholds of these gains. The results indicate that although the presence of a virtual body does not significantly affect the detectability of these gains, it supports users with the illusion of easier detection. We discuss the possibility of a future combination of full-body representations and redirected walking and if these findings influence the implementation of large virtual environments with immersive virtual body representation.

Keywords: redirected walking, body representation, curvature gain, translation gain

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1 INTRODUCTION

Virtual Reality systems provide an immersive experience for a user to perceive virtual environments (VE) with the help of a head-mounted-display (HMD). One challenge a developer has in creating VEs is the user navigation. VEs are often much larger than the available tracking space. Therefore, users quickly reach the borders of the tracking space while navigating by natural walking.

1.1 Gains Detection in Redirected Walking

Redirected Walking (RDW) [16] tries to overcome this limitation by subtly reorienting the user while they are moving with the help of gains, which function as a mapping between the users' real and virtual movement in VR. Two subtle continuous reorientation techniques which are used are rotation (g_R) and curvature (g_C) gain [23]. Rotation gain rotates the users' view depending on its head rotation. A subtle continuous repositioning technique used in RDW is translation gain (g_T) [23], which moves the users' view depending on his real movement. The real distance they moved is multiplied with a gain value g_T to calculate the virtual distance. After what Kruse et al. found, the range of the detection threshold for translation gain is smaller, when having a visually rich environment [10]. Curvature gain is used to rotate the users' view depending on their forward movement so that they have to physically reorient themselves to walk along a straight line in the VE.

According to Nilsson et al. the imperceptibility of the redirection is one of four criteria for an ideal RDW [14]. Several studies tried to find the detection thresholds to apply these gains with different conditions [2] [11]. Langbehn and Steinicke [12] listed some of these thresholds, where Steinicke et al. found that a translation gain between 0.78 and 1.22 [22] and Bruder et al. specified a curvature gain between $-3,84^\circ/\text{m}$ and $3,84^\circ/\text{m}$ (which is a radius of 14.92m) [2] are unnoticed by the user.

These reorientations without the user noticing it are possible, because the user tolerate a certain amount of difference between the visual and the proprioceptive perception in the VE without noticing a difference [16] [3] [9]. Is this difference too big, they notice the reorientation which can lead to a higher simulator sickness. Nguyen et al. showed that male subjects are more sensitive in detecting curvature gain and that a higher walking speed increases this sensitivity too [24]. According to Grechkin et al. the detection thresholds of curvature gain is not affected by the presence of translation gain [6]. They found a radius on a circular arc for curvature gain of 11.6m ($4,94^\circ/\text{m}$) or 6.4m ($8,95^\circ/\text{m}$) depending on the estimation method.

1.2 Self-avatar and Spatial Awareness

A virtual avatar could be described as a representation and the control of a body through a virtual reality device [4]. This can be only partially, like Kruse et al. who show the feet of the user [10], or the displaying of a self-avatar as a full-body illusion [4]. When implementing the latter, different approaches can be used to bring the users' movement to the virtual avatar. Spanlang used a motion tracking system to create an embodiment lab [21]. Roth et al. showed that an inverse kinematics approach with 5 trackers for each limb (feet, hands, head) is another good approach for body tracking which allows virtual embodiment and can reduce workload and latency compared to motion tracking [19].

A self-avatar can increase the sense of presence in a VE where Heidicker et al. showed that virtual body parts can increase this sense [7]. To increase this feeling further, Usoh et al. proposes the usage of an avatar which is as realistic as possible [25]. Self-avatars which are personalized and are visually similar to the user significantly increase body ownership, presence and dominance compared to a more generic avatar [26].

The spatial perception can be influenced by the presence of a self-avatar. Mohler et al. showed that an avatar experience can increase distance estimations in a VE [13], while Ogawa et al. showed with his experiment that object sizes are perceived as smaller only when having a realistic oversized hand model [15]. Ries et al. let users walk a specific distance blindly with and without a self-avatar. They found that users with a first-person avatar have a significantly improved distance perception inside the VE [17]. This shows that a self-avatar can affect the perception of the virtual self and virtual spaces.

1.3 Combine Embodiment with Gains

Kruse et al. researched the influence of visual body representation in the form of feet on the detection thresholds of translation gain [10]. They found no significant effect of virtual feet on this gain. Full-body representation and the effect of it on curvature gain was not tested in the experiment. Then again other studies showed that a self-avatar can influence how the virtual environment is perceived [13] [15] and that a self-avatar could improve the users' spatial perception [13] [17].

Since RDW manipulates the users' movement inside space and their perception of space and movement in it through a combination of visual and proprioceptive information is imperfect, such manipulations can remain undetected. That's why we designed an exploratory study to investigate, whether detection thresholds of translation and curvature gain significantly differ between full-body representation and no self-avatar at all. This paper shows the results of a psychophysical experiment, where the detection thresholds of translation and curvature gain are measured with and without a full-body representation and compared with each other.

The remainder of the paper is structured as follows. The following section describes the psychophysical experiment for determin-

ing the detection thresholds for curvature and translation gain with and without a self-avatar. The collected and analysed results of these experiments are shown, discussed and interpreted in section 3. The last section concludes the paper and possible future work is shown.

2 EXPERIMENT

In the following section we describe the experiments in which we measured the detection thresholds for translation and curvature gain with the conditions, where the user had either a self-avatar or no virtual self-representation at all. The following hypotheses will be tested with the experiment:

- H1: The detection threshold of translation gain is lower with a self-avatar than without it.
- H2: The detection threshold of curvature gain is lower with a self-avatar than without it.



Figure 2: Female and male Avatar for the body representation (Real-illusion Character Creator 3) [8]

2.1 Experimental Design

The experiment consisted of 4 sets of tasks, from which 2 sets applied translation and 2 sets applied curvature gain. For every set which was tested the same VE was used. It consisted of an area of an approximate size of 48m x 48m, which was delimited by houses. The inside of this area was completely empty to prevent the user from accidentally walking inside virtual obstacles. That's why there are less visual cues distracting the user while they are walking. The following 4 sets were executed:

- S1: No self-avatar with applying translation gain
- S2: Visible self-avatar with applying translation gain
- S3: No self-avatar with applying curvature gain
- S4: Visible self-avatar with applying curvature gain

For set 1 and 2 we tested 6 different translation gains $g_T \in \{0.7, 0.8, 0.9, 1.1, 1.2, 1.3\}$ and for set 3 and 4 we tested 5 different curvature gains (represented in $^\circ/\text{m}$) with left and right rotation for each gain which were $g_C \in \{-7, -6, -5, -4, -3, 3, 4, 5, 6, 7\}$ in $^\circ/\text{m}$ (amount of rotation in degrees for one walked meter). Therefore, gains which are both inside and outside of the noticeable range (as listed by Langbehn and Steinicke) were tested [12].

Each gain was repeated 5 times with a randomized order inside each set. S1 and S2 therefore involved a total of $(6 \times 5) = 30$ tasks each, and S3 and S4 involved a total of $(5 \times 5 \times 2) = 50$ tasks each. This results in a total of $((2 \times 30) + (2 \times 50)) = 160$ trials. For every

task the participant was randomly set to one of eight predefined locations inside the VE with a random rotation to avoid visual comparison to the previous task.

To prevent possible adaptation effects and possible dampening due to decreased sensitivity to the manipulation [1], the order of the executed sets were randomized for each user who took part in the experiment.



Figure 3: Users' POV with self-avatar and marker in sight.

2.2 Hardware and Software Design

All participants wore an HTC Vive HMD with a resolution of 1080 x 1200 pixels per eye and a diagonal field of view (FOV) of approximately 110°. The experiment was conducted in a laboratory room with the size of approximately 8m x 5m.

To track the users inside this room the lighthouse system from the HTC Vive was used which offered an available walking space of approximately 5m x 4m. Two HTC Vive controllers were used for input and to track the hands of the user and two HTC Vive trackers were additionally used to track the feet of the user.

The virtual scene was rendered using the Unity3D engine (version 2018.3.11). To map the avatar to the movement of the subject, the tracked objects were assigned to the corresponding limbs in VR and animated with inverse kinematics. For this the plugin "FinalIK" [18] was used. For the experiment we used a notebook with a 2.6 GHz, Intel Core i7 processor, 16GB of main memory and a Nvidia Geforce GTX 1070 graphics card.



Figure 4: Vive Tracker attached to the users' feet.

2.3 Experimental Task

Inside the given VE every user had to fulfill a set of tasks. At the beginning, they had to look at a red sphere which was placed 1m in front of them on the ground. That way we ensured that the user always had to look down and therefore had part of their avatar in sight while walking (see Figure 3). Now they had to start the task by pressing a button on the controller. After a countdown the sphere turned green and started to move. The subject had to follow the sphere with a real-world velocity of 0.7 m/s. While doing that the current gain for the set was applied to their movement.

After walking 5 meters in reality, the sphere stopped and the users had to answer a question as a two-alternative-force choice (2AFC). After answering the question, every visible body part and applied gain was disabled. That way the user were less able to compare the current and the next used gain with each other. They had to turn around and walk back to the starting point (represented by a blue circle). Then they turned around again, pressed a button on the controller and were randomly placed on one of the predefined locations, which lead to a new VE for the user for the next task. This was done to prevent visual comparison between the tasks. After that, the next task started.

2.4 Data Collection and Analysis

During the experiment several data were collected. At the beginning and after the experiment every user had to fill out a simulator sickness questionnaire (SSQ) [20] and some demographic data were collected (age, course of studies, height, experience with VR). After walking while applying the gain, the user had to answer a question. In set 1 and 2 (where translation gain was applied) they were asked whether their virtual movement was slower or faster than their physical movement. In set 3 and 4 (where curvature gain was applied) they were asked if they walked on a left or right curved path in the real world. The answer "equal" was not available to avoid a bias which would be caused by the user being influenced by this choice. When they could not definitely identify the right answer they had to guess, which lead to a 50/50 chance to get the answer correct.

The answers were summarized by calculating the mean value for each gain which were then fitted with a sigmoidal psychometric function. These are displayed with their corresponding standard errors in Figure 5. This function intersects with 3 lines representing the following:

- 25% line: Lower Detection Threshold (LDT) for the gain
- 50% line: Point of subjective equality (PSE) for the gain
- 75% line: Upper Detection Threshold (UDT) for the gain

Gains which lie between the 25%- and the 75%-line (i.e. the LDT and UDT) are not reliably detected by the user and can therefore be used for redirected walking [22].

2.5 Participants

A total of 17 subjects participated in the experiment. The average age was 23.24 years (18-30y) with 14 male and 3 female participants. The average height of the subjects was 1.78m (1.65m -1.95m). 7 subjects had some experience with VR, 7 participants had much experience with VR and 3 subjects never had worn an HMD before. All subjects had normal or corrected-to-normal sight. With briefing, the general questionnaire, simulator sickness questionnaires, breaks and the experiment, the total time per subject was around one and a half hours.

2.6 Procedure

After filling out the first questionnaires (SSQ and demographic data), the user were equipped with all trackers and were told, how the general procedure of one set was. To get to know the task, the subjects were able to test the procedure for both gains several times. At the beginning of every set the user were positioned in one corner of the tracked space and, depending on the visibility of the avatar, the avatar was calibrated to the trackers and was scaled properly to the users' height. There were two avatars, one male and one female (see Figure 2), which was selected depending on the subjects' gender.

After every set they were allowed to take a short break. In the end, the participants were told what the goal of the experiment was and they were asked to fill out another SSQ. This procedure was adopted from previous experiments from Kruse et al. [10] and Steinicke et al. [22].

3 RESULTS

All collected results for each set of tasks can be seen in Figure 5. The exact intersection points of the psychometric function and the lines can be found in Table 1 together with the differences of the thresholds between the sets. To run significance tests we calculated the individual LDT, PSE and UDT for each participant. A Shapiro-Wilk normality test shows that these values are not normally distributed, which is why we run a total of six Wilcoxon signed rank tests at a 5% significance level comparing the pairs of LDTs, PSEs and UDTs for both translation and curvature gain. These results can be found as p-values in Table 1.

Translation Gain Results Figure 5a and 5b show the plotted results for set 1 and 2 for applying translation gain with and without showing a self-avatar. The x-axis shows the translation gain values $g_T \in \{0.7, 0.8, 0.9, 1.1, 1.2, 1.3\}$ and the y-axis shows the probability of the user selecting the answer "Faster" for the applied gain.

We observe a 2% lower LDT ($p = 0.6527$), a 4% lower PSE ($p = 0.0750$) and a 5% lower UDT ($p = 0.1936$) when having an avatar. Since the Wilcoxon signed rank test does not reveal p-value below the 5% significance level, no significance can be shown and therefore the hypothesis H1 cannot be confirmed.

Curvature Gain Results The results for set 3 and 4 can be found in Figure 5c and 5d. The x-axis again shows the gain values (here curvature gain: $g_C \in \{-7, -6, -5, -4, -3, 3, 4, 5, 6, 7\}$) and the y-axis the probability of the participant choosing the answer "Left" for the applied gain.

We examine a 1% lower LDT ($p = 0.7188$), a 55% lower PSE ($p = 0.6892$) and a 17% lower UDT ($p = 0.7565$). Although the difference between the PSE and UDT is slightly notable, the p-values are again not below the significance level, whereby no significance in these results can be shown and again hypothesis H2 cannot be confirmed.

With these results, the conclusion of Kruse et al. [10] can be confirmed, where the effect on the detectability of translation gain with showing virtual feet could not be shown. We can extend this by showing that an effect of a self-avatar on translation and curvature gain cannot be confirmed.

An additional interesting fact is that although the results imply no effect on the detectability of these gains, subjective perception of the participants supposes something different. All participants were asked whether they found it easier or harder to detect the applied gain with the full-body representation. 12 out of 17 participants (71%) had the subjective feeling that it was easier for them to detect.

Table 1: Detection thresholds and PSE for all sets, as well as differences and the Wilcoxon p-value.

Translation Gain	LDT	PSE	UDT
Without Body (S1)	0.911	1.091	1.278
With Body (S2)	0.891	1.049	1.216
Difference	0.020	0.042	0.063
p	0.653	0.075	0.194
Curvature Gain	LDT	PSE	UDT
Without Body (S3)	-5.518	-0.703	4.124
With Body (S4)	-5.590	-1.087	3.428
Difference	0.072	0.384	0.696
p	0.719	0.689	0.757

3.1 Result of the SSQ

The SSQ comprises three groups: Nausea (N), Oculomotor (O) and Disorientation (D), which all consist of the sum of the results of the associated questions [20]. The total score is calculated by the sum of these groups multiplied by a weight factor. The results of the simulator sickness questionnaire show a mean total score of 15.194 before the experiment with a standard error of 4.429. After the experiment the score raised to 26.18 with a standard error of 7.098. A Shapiro-Wilk normality test shows non-normally distributed values. So again a Wilcoxon signed rank test at a 5% significance level was chosen. The test reveals a value of $p = 0.0264$, which shows a significant effect of the experiment on the feeling of simulator sickness of the participants. On average each user spent about 75 minutes in VR during the experiment.

3.2 Discussion

The results reveal no significant differences on the detection thresholds of both tested gains. Set 1 & 2 show that the thresholds had at most 5% difference. No significance can be shown, so an effect of a self-avatar on the detection thresholds of translation gain could not be shown. Both sets needed a little faster virtual movement (factor 1.04-1.09) compared to the real velocity to appear natural for the user. Other findings confirmed this result, where users are more likely to underestimate travel distances in the virtual world [22] [5]. Set 3 and 4 reveal almost similar LDT and a higher UDT (with a difference of 0.7) for curvature gain when a self-avatar is present. Since a statistical test could not confirm a significant difference between the thresholds, we cannot confirm H2. For the movement to appear natural, the user had to be rotated $-1.09^\circ/\text{m}$ without and $-0.7^\circ/\text{m}$ with the presence of an avatar. The reason for these deviations from $0^\circ/\text{m}$ were not examined in this paper and could be the topic for future research.

Our results were in line with the findings of Kruse et al. [10] and extend it by their proposed future work by extending their experiments with a full-body avatar and by curvature gain. We can suppose that embodiment in virtual reality does not have a significant effect on the detectability of translation and curvature gain. The fact that users subjectively found the gains easier to perceive could be supporting for our hypotheses. Since we cannot confirm these it could imply that the user felt something different than it actually was. This could be possible, because the user suspected something to be different in their perception. In reality, the results showed that without a body these gains were almost as perceivable as with the self-avatar. The measured offset (i.e. UDT at set 3 and 4) could be caused by the effect of body representation on perception of size and distance [15] [13].

The SSQ results indicate that cybersickness significantly increased during the experiment, which could be possible because of a discrepancy between visual and proprioceptive information. Further

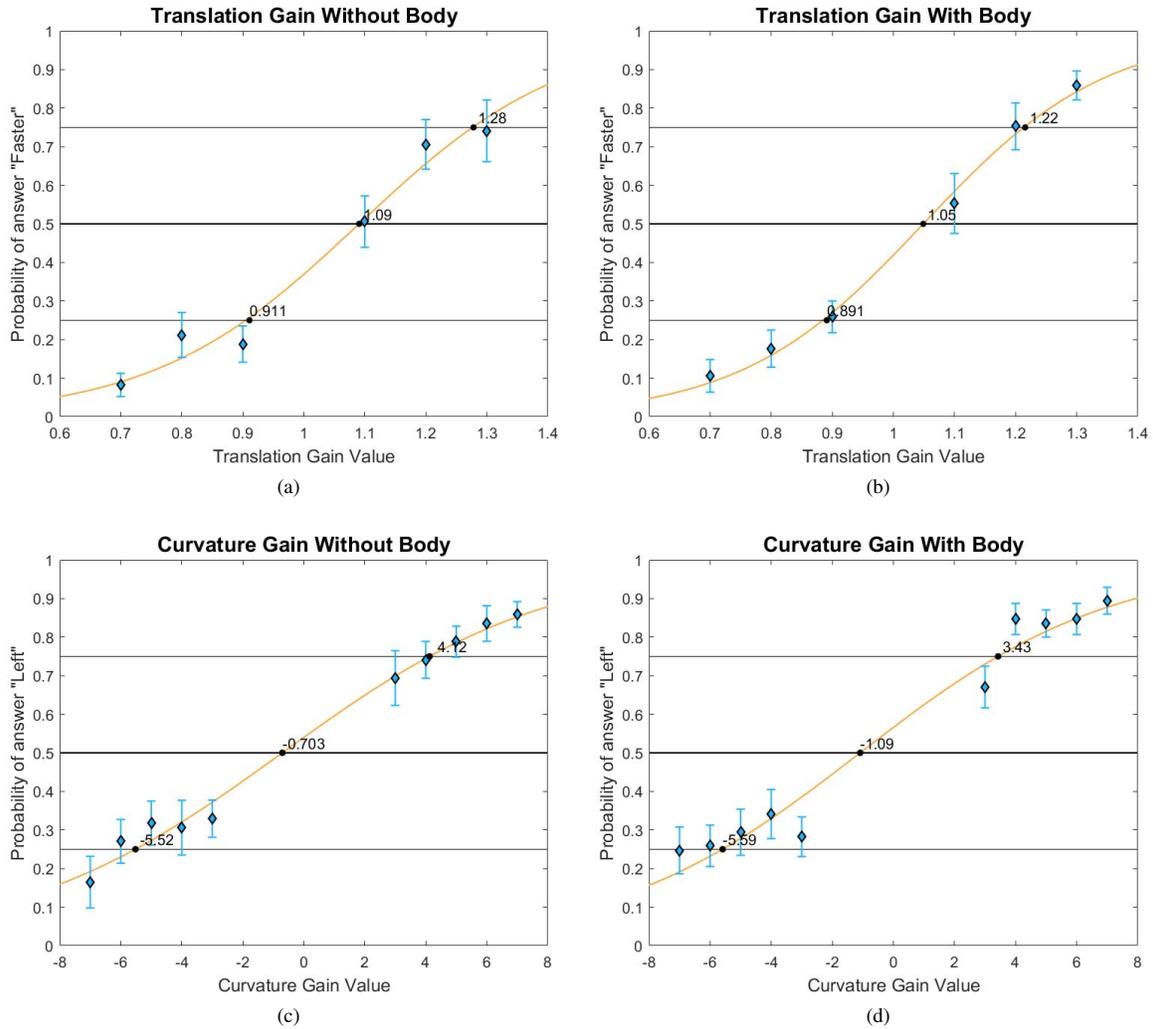


Figure 5: Results for translation & curvature gain without (a) & (c) and with (b) & (d) self-avator, together with detection thresholds, PSE and a sigmoidal psychometric function. The x-axis is the applied gain, the y-axis shows the probability of the user answering "Faster" or "Left" when applying the gain.

experiments with measuring the cybersickness for each gain is needed to confirm this theory.

In conclusion, we showed that the presence or absence of a self-avator has no significant effect on the detection thresholds of translation and curvature gains, which indicates a negligible effect of the self-avator on RDW.

4 CONCLUSION

In this paper we conducted an experiment, to figure out whether the virtual representation of a self-avator has an effect on the applicability of translation and curvature gain. For this we conducted a psychophysical experiment where we prepared 4 sets of tasks. Two sets where translation gain $g_T \in \{0.7, 0.8, 0.9, 1.1, 1.2, 1.3\}$ was applied with and without a self-avator and two sets where curvature gain $g_C \in \{-7, -6, -5, -4, -3, 3, 4, 5, 6, 7\}$ was applied (with and without a virtual body). The results revealed no significant differences in the detection thresholds, when a full-body representation was present. That confirms and extends the results of Kruse et al. [10] and can assist future developers that embodiment in virtual reality can be further used and implemented without the need to

relinquish RDW. It is possible that immersive self-avatars could be used without the cost of having higher or lower detection thresholds for translation and curvature gain. Although we could not find any significant differences, this paper fills a gap in the literature about RDW with full-body representation.

Further research on the impact of embodiment on a full RDW, where translation, curvature and rotation gain are applied simultaneously would be interesting in the future.

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