# Effect of Sense of Embodiment on Curvature Redirected Walking Thresholds

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## ABSTRACT

Redirected walking (RDW) allows users to explore a virtual environment larger than the physical tracking space by real walking. When RDW is applied within certain thresholds, users do not notice it and remain immersed in the virtual environment. There are many factors that affect these thresholds such as walking speed, gender, and field of view. However, redirected walking thresholds (RDTs) were never studied when an avatar is present, and it is not known how the sense of embodiment over this avatar affects users' RDTs.

In this paper, we present an experiment to investigate the effect of sense of embodiment (SoE) of an avatar on curvature RDTs. The SoE was manipulated by changing perspective as well as sensorimotor congruency and subjectively assessed using an SoE questionnaire. Results showed perspective and movement congruency have significant effects on the SoE, and that agency, which is a central component of embodiment, has a negative effect on curvature RDTs. Moreover, existing results on gender effects on RDTs were also reconfirmed.

## CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Virtual reality**; • **Applied computing** → **Psychology**;

## KEYWORDS

sense of embodiment, perspective, movement congruency, redirected walking, redirection threshold, virtual reality

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## 1 INTRODUCTION

Up to now, no other navigation techniques have been able to compete with real walking in terms of feeling of presence [32, 36], way finding, and distance estimation [22, 28]. However, the problem with real walking is that the virtual environment is most of the time much larger than the available tracking space. One approach to tackle this problem is called redirected walking (RDW) [25]. This approach focuses on manipulating the mapping between the virtual and physical trajectories of the user by providing them with conflicting visual and vestibular information. By injecting continuous rotation and/or translation to the virtual camera, users would walk on a different curvature in reality compared to in VR - curvature gain; rotate less or more in reality than in VR - rotational gain; or walk faster or slower in reality than in VR - translational gain. When applied within certain thresholds, this manipulation is not noticeable to the users and immersion remains intact.

Various research groups have attempted to quantify these thresholds [1, 31] and different factors that influence them. It has been found that gender significantly affects redirected walking thresholds (RDTs), specifically men are more sensitive than women in detecting curvature gain [20, 27] and rotational gain [34]. Walking speed has been consistently shown to be negatively correlated with curvature RDTs [17, 20]. A larger field of view allows a wider range of rotational gain to go undetected [35]. Although environment size and visual density have been observed to have an effect on curvature gain and rotational gain [8], in other experiments the effects were not confirmed [19, 21]. In another study, the impact of seeing one's own feet on translational RDTs was investigated [11]. No significant difference in translational RDTs between the seeing feet and no feet conditions was found. Even though quite some effort has been spent on investigating factors affecting RDTs, in none of these existing studies a virtual representation of the user's whole body was present. It has been shown that stronger feeling of embodiment over a virtual avatar affects user's spatial perception and reduces distance underestimation in VR [6, 15, 24, 26]. Nevertheless, in the context of RDW, the effect of sense of embodiment (SoE) on how redirection perception has never been explored.

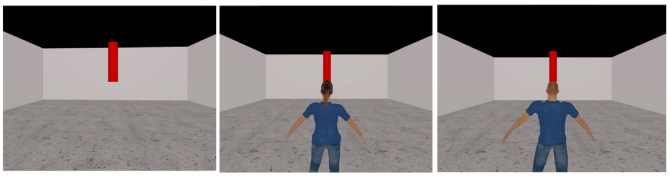
In this work, we set out to investigate the effect of SoE on curvature RDTs. The question being raised here is: how does an increased SoE affect the perception of the virtual environment (VE) during RDW? We hypothesized that a stronger SoE leads to a stronger reliance on the visual information from the VE and consequently makes users more susceptible to the "manipulation". To answer this question, we first looked into existing literature on how the SoE could be modulated and then performed an experiment to identify users' curvature RDTs under different SoE conditions.

## 2 RELATED WORK

The SoE over a virtual body can be separated into three distinct components: a) the sense of self-location: the sensation that one's own body is being located where the virtual body is, b) the sense of agency: the sensation of having motor control over the virtual body, and c) the sense of body ownership: the sensation that the seen virtual body is one's own [10]. Various aspects of the virtual body have an influence on the SoE. For example, the avatar's appearance and level of realism have been shown to affect the sense of body ownership and how conflicting cues are perceived [14]. More specifically, when the avatar has a more human-like body as compared to a plastic mannequin, subjects had a more convincing illusion that the body was their own, and the incongruent cues were not detected as incorrect. The congruency between subject's performed motion and the visual motion seen on the avatar is also a relevant aspect to the SoE. Liang et al. have termed this congruency as visual agency [13]. In other words, when the movement of the observed virtual body corresponds correctly to a person's own real movement, they feel that they have visual agency over that virtual body. Visual agency has been shown to improve the sensation of ownership of a virtual hand in the rubber hand illusion [3, 9] and even could induce a feeling of agency over the body of someone else when that person performs the same body movement as oneself [23].

Another important aspect that contributes to the SoE is the perspective with which the virtual body is viewed. In the first person perspective (1PP), the virtual body is located at the same position as the subject. In the third person perspective (3PP), the virtual body is located away from the subject and they view the virtual body from above [29], behind [5, 7], or to the side [30]. It has been shown that subjects felt a stronger sense of body ownership and self location in 1PP compared to 3PP, but there was no significant difference in the sense of agency [7, 30]. In a drawing task where subjects were asked to draw vertical lines while looking at a virtual hand performing the motion, subjects were more "manipulated" by the deviation from the straight path of the virtual hand in 1PP than in 3PP [2]. It could possibly be inferred that the stronger sense of body ownership in 1PP leads to being more easily "manipulated", which also agrees with findings from Maselli et al. [14].

All existing works point to the fact that a higher SoE could lead to higher RDTs. In the context of RDW, the work in the most similar direction is a study by Kruse et al. which investigated the effect of looking at one's feet while walking on the detection threshold of translational gain [12]. No significant effect of the presence of the feet on translational RDTs was found. However, the presence scores for the seeing feet and no feet conditions were not significantly different, and thus a conclusion could not be reached about the effect of SoE.



**(a) 1PP** **(b) 3PP female** **(c) 3PP male**

**Figure 1: Location of the virtual camera in the 1PP and 3PP conditions**

Based on existing findings about how the SoE is affected by different virtual avatar aspects, we selected the two prominent factors that can be used to regulate the SoE: the congruency between the subject's virtual and real body movements and subject's viewing perspective on the avatar. Our first hypothesis is that movement congruency and perspectives have significant effects on SoE. We also hypothesize that curvature RDTs are higher when the avatar body movement is congruent with subject's body movement than when it is not; and that curvature RDTs are higher when the avatar is viewed in 1PP as compared to 3PP.

## 3 EXPERIMENT DESIGN

To limit the effect of other external factors on RDTs, the virtual environment was composed of an empty room of 10m by 10m and a red cylinder used as the target, located 7.5m away from subjects' starting position (Figure 1a). Before the experiment, subjects's heights were collected and a gender-matched avatar was created for each subject corresponding to their height (Figures 1b and 1c).

The experiment consisted of two perspective conditions (1PP and 3PP) and two avatar body movement congruency conditions (congruent and incongruent). In the 1PP condition, the virtual camera was located at the same location as the virtual avatar's head (Figure 1a). When the subject looked down, they could see their body located at the same place as their physical body. In the 3PP condition, the virtual camera was located 2m behind and 1m above the virtual avatar such that the whole avatar's upper body was visible (Figures 1b and 1c). Originally, the 3PP was designed such that the rotation of the subject's physical body would result only in the rotation of the virtual body and subjects always saw the virtual avatar in front of them. However, out of the four pilots subjects, while two had no problem completing the whole experiment, two suffered from severe motion sickness very early on in the 3PP condition. Due to this extreme reaction, the 3PP condition was redesigned, and the rotation of the subject's physical body would result in the rotation of both the virtual body and the virtual camera around their own axes. For both conditions, when a curvature gain was applied, the whole environment was rotated around the virtual camera position. In the congruent condition, the avatar body movement followed subjects' physical body movement. In the incongruent condition, the avatar body movement was pre-animated and did not follow the subjects' physical body movement.

The experiment set-up consisted of an Oculus DK2 with a built-in SMI eye tracker and an Intersense IS-1200 inside-out optical tracking system mounted on top, providing 6-DOF positional tracking at 180Hz in a tracking space of 13.3m × 6.6m. A cover was added in front of the headset to prevent users from seeing the floor. To track subject's body movement, a 32-sensor Noitom motion capture suit was used. Using coordinate transformations, the hip position was controlled by the data obtained from the Intersense head tracking, while the rest of the body movement was controlled by the data from the motion suit.

## 4 PARTICIPANTS AND PROCEDURE

Thirty subjects (aged from 21-34 (mean=25.5, sd=3.3), 15 men and 15 women, right-handed, with normal or corrected-to-normal vision) participated in the experiment. After having signed the consent form and understood the procedure of the experiment, the subject put on the motion suit, the backpack with the attached laptop, and the HMD. Each subject was exposed to three conditions congruent 1PP (*1PP_congruent*) , congruent 3PP (*3PP_congruent*) and incongruent 3PP (*3PP_incongruent*), performed in three separate blocks. The incongruent 1PP condition was not included as the incongruency cannot be observed while walking in the 1PP. The order of all three conditions was randomized for each subject to counteract learning effects. Each block was carried out with the following procedure:

- Pre-experiment questionnaire: subjects filled out the Simulator Sickness Questionnaire (SSQ).
- Calibration (~2 minutes): subjects performed predefined poses to calibrate the motion suit. As tracking quality worsened over time, recalibration had to be performed again every five walks.
- Familiarization (~3 minutes): subjects saw themselves in an empty room and were asked to look around and familiarize with their virtual body. The purpose of this step is for subjects to establish a sense of ownership and agency over the virtual body that they see (wherever it is possible). While standing on the spot, subjects were asked to raise their arms and legs, and observe the virtual body accordingly.
- Training (10-15 minutes): The purpose of this phase is to familiarize subjects with the threshold identification procedure, how redirection should feel and how to control the virtual avatar while performing locomotion. A strong level of curvature gain was selected (gain = 0.25) such that subjects would certainly recognize the manipulation. The training phase ended once the subject had selected the correct answer three times in a row.
- Experiment (~25 minutes): A two-alternative force-choice (2AFC) task was used where subjects performed two walks in each trial. In only one walk a non-zero curvature gain was applied. At the end of the two walks, subjects answered to the question: *"In which walk were you redirected: first or second?"*. Depending on this answer's correctness, the next curvature gain (with value ranging between 0 and 0.25) was calculated based on an adaptive Bayesian method called QUEST [33]. Subjects performed in total 25 trials for each condition.
- Post-experiment questionnaires: subjects filled out the SSQ again. To assess the effectiveness of different perspective and congruency conditions on the feeling of presence, we proposed a questionnaire where user could give a subjective rating on the virtual avatar. The SoE questionnaire consists of five 100-point Likert scale questions adapted from work by Debarba et al. (from 0 point (strongly disagree) to 100 point (strongly agree)) about different aspects of the virtual avatar [4]:
  - Agency: It felt like I was in control of the body I was seeing
  - Body ownership: It felt like the virtual body was my own body
  - Self location: It felt as if my body was located where I saw the virtual body to be.
  - Multiple bodies: It felt as if I had more than one body
  - Presence: It felt like I really was in the virtual room.

## 5 RESULTS AND DISCUSSION

For each subject, three threshold values were obtained corresponding to the three conditions: *1PP_congruent*, *3PP_congruent* and *3PP_incongruent*. Overall, threshold values ranged from 0.018 to 0.24 (equivalent to curvature radii of 55.5m to 4.17.m) with mean = 0.14, sd = 0.04 (7.14 m curvature radius). This wide range of RDTs support findings in previous studies that users' sensitive to curvature RDW varies significantly [20]. Subjects' walking speed ranged from 0.77m/s to 1.37m/s (mean = 1.04m/s, st = 0.14m/s). SSQ scores before and after each condition were calculated by adding all subscores with equal weighting of one and the SSQ score difference between pre- and post- condition was obtained (mean = 2, st = 2.9). As it has been shown in previous studies that 3PP helped reduce simulator sickness [16], a linear mixed model was fitted with the SSQ score difference as the dependent variable, perspective (1PP vs. 3PP), congruency (congruent vs. incongruent) and gender as independent variables and subject as a random variable. Contrary to existing findings, our result showed no significant effect of perspective on the SSQ score difference. There was also no significant effect of either gender or congruency. One possible explanation for this result is that even though subjects' exposure time in VR in Monteiro et al. was much shorter (~ 11 minutes per condition), the VR application used was a racing application with fast movements and rich optical flow, which could induce more simulator sickness.

To investigate if the different perspectives and congruency conditions had an effect on the SoE, mixed linear model analyses were ran for each component of the SoE questionnaire: sense of agency, sense of body ownership, sense of self location, sense of multiple body and feeling of presence with the score as dependent variable, condition (*1PP_congruent*, *3PP_congruent* and *3PP_incongruent*) as an independent variable and subject as a random variable. For each score, pairwise comparisons between the conditions were carried out. The resulting p-values were corrected for multiple comparisons using the Bonferroni correction (Figure 2)

*Agency score.* No significant difference was found between *1PP_congruent* and *3PP_congruent* or *1PP_congruent* and *3PP_incongruent*. This result is in line with existing findings that perspective does not have a significant effect on agency [7]. However, a significant difference in agency score was found between the *3PP_congruent* and *3PP_incongruent* conditions (p=0.0027). Agency describes the feeling of control over the virtual avatar, and therefore this result showed that the use of an animated avatar has achieved the desired effect of lowering subjects' sense of agency over the virtual body.

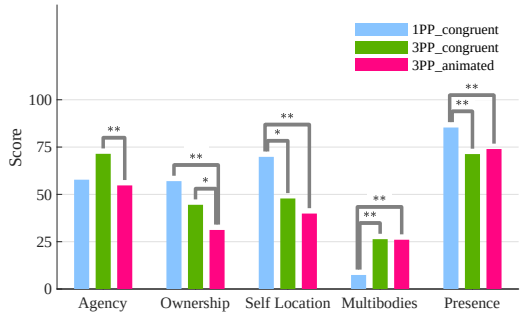



**Figure 2: The SoE sub-scores**
*** and ** correspond to p<0.05 and p<0.01 respectively.**

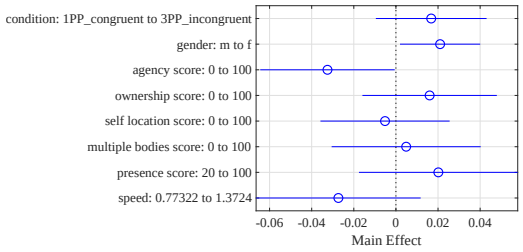



**Figure 3: Effects of gender, speed and SoE scores on RDTs**

*Body ownership score.* There were significant differences in body ownership scores between the congruent conditions and the incongruent condition, specifically, between *1PP_congruent* and *3PP_incongruent* (p=0.0071) and *3PP_congruent* and *3PP_incongruent* (p=0.036). This result also showed that the use of the animated avatar was effective in creating a significantly different sense of body ownership between the different congruent conditions.

*Self location score.* There were significant differences in self location scores between the 1PP condition and the 3PP conditions, specifically, between *1PP_congruent* and *3PP_congruent* (p=0.034) and between *1PP_congruent* and *3PP_incongruent* (0.0037). This result showed that different perspectives have significant influence on the subjects' feeling that their body is located at same location as the virtual body. For the case of the *3PP_congruent* condition, they do not feel that they are located at where the virtual body is seen, despite feeling agency over this body.

*Multiple bodies score.* Even though subjects did not identify their body to be located at the location of the virtual avatar in the 3PP conditions, their scores in feeling like they have more than one body in the 3PP conditions were significantly higher than the 1PP condition (p=0.0021 and p=0.0057 for the *3PP_congruent* and *3PP_incongruent* conditions, respectively). This result shows that, to some extent, subjects also felt a sense of ownership over the virtual body that they see in *3PP_incongruent* condition. This is probably due to the fact that even though body movement of the avatar was completely different from the subjects' body movement, its position and rotation still follow subjects' position and rotation.

*Feeling of presence score.* The feeling of presence was significantly higher in the 1PP condition compared to the 3PP conditions (p = p = 0.0027 and p = 0.0016 for the *3PP_congruent* and *3PP_incongruent* conditions, respectively). This shows that perspective plays an important role in eliciting the feeling of presence, and agrees with previous study on how users perceive threat to the body more acutely when they view the virtual body in 1PP [14].

In summary, the use of different viewing perspectives and congruency conditions of the virtual avatar has achieved the desired effect of eliciting significant difference in the feeling of agency (congruent vs. incongruent), body ownership, self location, multiple bodies and feeling of presence (1PP vs. 3PP).

To examine our hypothesis about the effect of SoE on how subjects perceive RDW, a linear mixed model analysis was constructed with RDTs as the dependent variable, gender, walking speed, conditions (*1PP_congruent*, *3PP_congruent* and *3PP_incongruent*) and the embodiment sub-scores as independent variables, and subject as a random variable. The main effects of the independent variables in this model can be found in Figure 3. Gender was again shown to have a significant effect on RDTs, particularly, women on average have higher RDTs than men (p = 0.04). A significant effect of walking speed on RDTs has not been found. This is an interesting result, as speed has been shown to be a consistent factor that influences RDTs [18, 20]. It is, however, important to note that individual thresholds vary significantly, and since in this experiment speed was not a controlled within-subject factor, the effect of speed could have been masked by the high variability of RDTs across individuals. Out of all embodiment scores, agency score was the only factor having a significant effect on RDTs (p = 0.03). While existing works lean towards the fact that a strong feeling of agency causes the subject to perceive less cue conflicts [14], our results show a significant effect in the opposite direction. There is a negative correlation between agency score and RDTs, i.e. in conditions where subjects have stronger feeling of agency over the virtual body, they tend to detect redirection better. This difference could be due to the different nature of the cue conflicts in existing works and our work. The cue conflicts in existing works involve mainly visual-proprioceptive conflicts in the ego-centric frame, while the cue conflicts in the case of RDW involve mainly visual-vestibular conflicts in the inertia reference frame. The mechanism of detecting these conflicts may be different, and while in one case being immersed may make it harder to detect conflicts, in the other case, being immersed enables users to be more sensitive.

## 6 CONCLUSION AND FUTURE WORK

In this work, we studied the influence of SoE on curvature RDTs. Results showed that out of all SoE sub-scores, agency score was the only factor with a significant effect on curvature RDTs, specifically, the stronger sense of agency enables the subjects to detect RDW better. This result implies that curvature gains should be carefully selected for future RDW applications where users report strong sense of agency over the avatar.

Our study also confirms existing results on impacts of perspectives and body movement congruency on the SoE. Specifically, 1PP is generally superior when feeling of presence and sense of self location and body ownership is concerned. Therefore, despite the fact that spatial awareness is better in 3PP [7], 1PP should still be the preferred perspective to experience an immersive environment.

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