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Redirected Walking in Place

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Abstract

This paper describes a method for allowing people to virtually move around a CAVE™ without ever having to turn to face the missing back wall. We describe the method, and report a pilot study of 28 participants, half of whom moved through the virtual world using a hand-held controller, and the other half used the new technique called 'Redirected Walking in Place' (RWP). The results show that the current instantiation of the RWP technique does not result in a lower frequency of looking towards the missing wall. However, the results also show that the sense of presence in the virtual environment is significantly and negatively correlated with the amount that the back wall is seen. There is evidence that RWP does reduce the chance of seeing the blank wall for some participants. The increased sense of presence through never having to face the blank wall, and the results of this pilot study show the RWP has promise and merits further development.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interfaces and Presentation]: Artificial, Augmented, and Virtual Realities

1. Introduction

There are many different techniques for allowing participants to move about[1] in human-scale, immersive virtual environments (VEs). Such movement of the participant is an important interaction in any VE. Techniques include 'flying' with a joystick [1], using a treadmill [2-5], Walking in Place [6, 7], leaning [8, 9] and many others [9-12]. The choice of movement technique significantly affects the participant's experience, sense of presence [12, 13] and, we believe, the level of simulator sickness. Presence, the subjective feeling of being in the VE, is important for many VE applications [14], while simulator sickness is a serious 'show stopper' for many participants [15].

The most common method of movement in CAVEs™[2] is to fly using a joystick or wand. Many participants have trouble adapting to this and find it distracting [12]. Other research shows flying with a joystick results in a lower sense of presence than walking in place [6]. Holding the joystick is also an added encumbrance since the participant can no longer use that dominant hand for other tasks. In pursuit of a more natural, easier to learn and more presence inducing method of movement in a CAVE™, we are developing a new technique: Redirected Walking in Place (RWP).

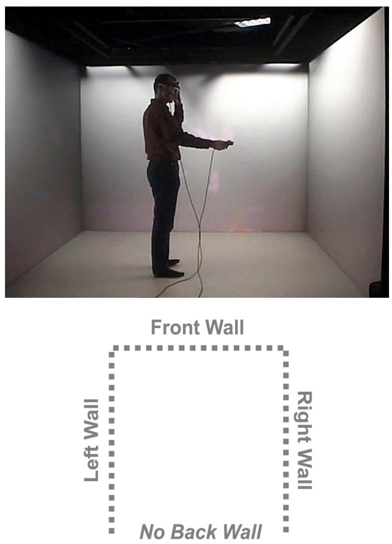

Figure 1: *A photograph and overhead diagram of a CAVE™ with an open back wall.*

[1] This refers to local movement within the VE, as opposed to way finding or navigation which is a higher-level cognitive task.

[2] CAVE™ is a registered trademark of the University of Illinois' Board of Trustees. We use the term to generically refer to CAVEs™ and CAVE-like displays.

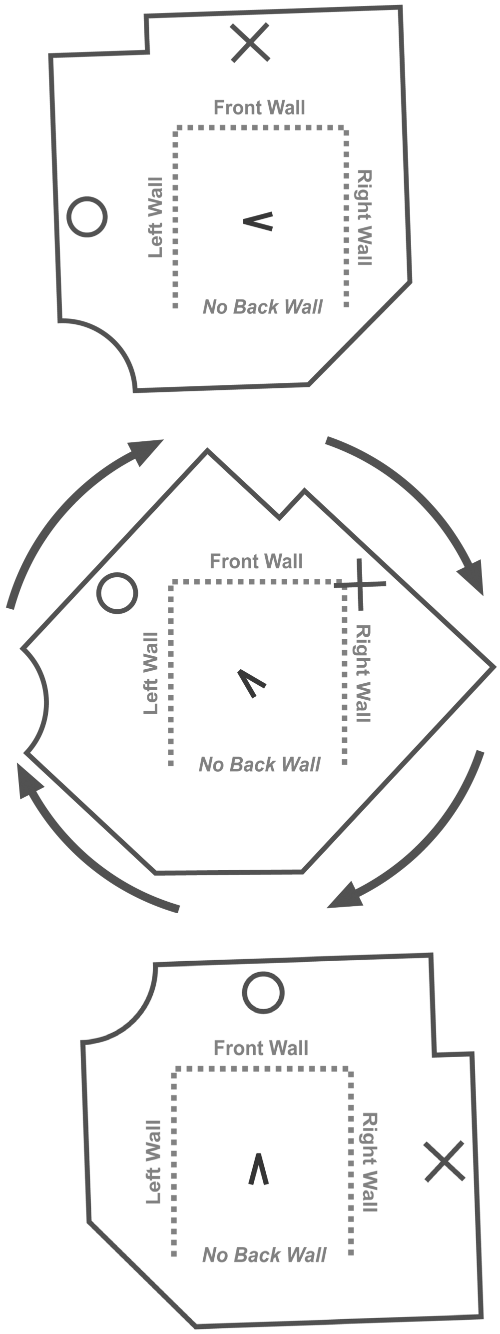

Figure 2: *Overhead diagrams of the CAVE™ (dashed line) and an example VE (solid dark line) with a 'O' and 'X' as landmarks. Initially the participant (shown as a small arrow in the centre) is facing the left CAVE™ wall, towards the 'O' in the VE. We slowly and imperceptibly rotate the VE to the right such that the 'O' is now projected onto the front wall. The participant unknowingly rotates herself towards the front wall as well.*

Redirection (causing the participant to physically turn without her noticing that she is turning) has been successfully demonstrated with wide-area trackers and head-mounted displays [16]. However, the number of facilities with such equipment is currently very small, perhaps less then 10. CAVEs™ are much more common – there are approximately 600 CAVEs™ as of today [17]. Walking in Place has been demonstrated with a HMD VE system but cannot be directly applied to most CAVEs™ since they do not completely enclose the participant, the back wall being open (fig. 1). With Walking in Place in a CAVE™, the participant must still turn in the VE using a joystick.

Traditionally, if a participant wishes to move towards an object in the VE, she must first rotate the VE using a joystick or other hand controller so that the virtual object is in front of her. Previous research shows a positive correlation between appropriate body movement and presence [13]. This suggests that a participant who turns her body is more likely to be present. With redirected walking in place (RWP), our goal is to allow the participant to turn in the VE by turning her body instead of using a joystick.

The problem with turning the body is that the vast majority of CAVEs™ have only three vertical walls [17](fig. 1). If the participant turns with her body, she will eventually face the open back wall. With RWP, we slowly and imperceptibly rotate the VE while the participant is walking in place so that she is made to turn towards the front wall of the CAVE™ without noticing (fig. 2). A participant can virtually walk in a full circle without turning towards the empty back wall.

Implementation of Redirection

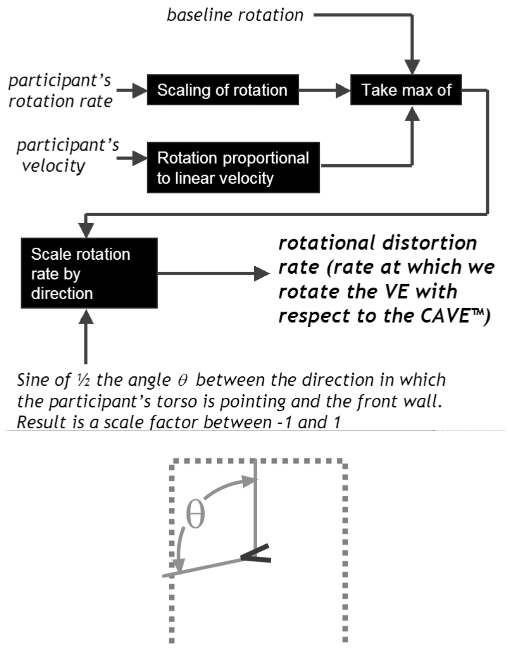

Figure 3: *The algorithm to calculate the rotation rate*.

Our algorithm determined the VE's rate of rotation based of several inputs: the participant's orientation (with respect to the front wall), angular head velocity, and virtual walking speed. It employed three separate components of rotation. First, it injected a small baseline amount of rotation. Thus even when the participant was standing still, the room rotated slowly (until the participant faced the front wall). Second, it injected a greater amount of rotation when the participant was walking in place. Finally, when the participant turned herself (a higher frequency motion) we injected additional rotation proportional to the participant's angular velocity. The particular constants and weights we used are listed in appendix A.

The rotation applied in any frame was the maximum of the above three components: constant baseline rotation, constant rotation when walking in place, and rotation proportional to the participant's angular velocity.

This rotation angle was multiplied by a 'direction coefficient' so that we rotated the VE in the proper direction. When the participant was facing to the right of the front wall, the VE was rotated to the left. When the participant was facing to the left, the VE rotated to the right. This 'direction coefficient' was calculated by computing the sine of half the angle[3] between the participant's torso in the CAVE™ and the front wall of the CAVE™ (fig. 3). This caused the rotation rate to be greater when the participant was facing further from the front wall, and zero when the participant was facing straight ahead.

We rotated the VE about the centre of the participant's head, not the centre of the CAVE™.

3. Theory

Redirection works by interactively rotating the virtual scene about the participant, such that the participant is made to continuously turn towards the front wall of the CAVE™. The participant does not notice this rotation because the algorithm exploits the limitations of human perception for sensing position, orientation and movement. The amount of rotation is a function of the participant's orientation, linear velocity, and angular velocity.

Humans rely primarily on vestibular and visual cues for balance and orientation [18]. Humans also use these senses to determine whether they themselves are moving (self-motion) or if the objects around them are moving (external-motion). Previous research suggests that keeping multiple cues consistent increases the chance that the participant will perceive rotation as self-motion as opposed to external motion[19]. If Redirected Walking maintains consistency between visual and vestibular cues, the participant should not sense the world moving arbitrarily around her. The goal is to maximize the probability that all of the participant's perceived motion is self-motion.

Each ear's semi-circular canals act approximately as three orthogonal rotational rate gyros; they sense the high-frequency components of a person's angular movement. The visual system senses low-frequency components. Because our VE system does not employ devices that induce vestibular cues, such as a motion platform, we avoided high-frequency rotations.

Even while standing still, the participant unknowingly rotates her head and torso with the virtual scene. We hypothesise that the participant's own balance mechanisms are responsible for this [18]. While walking in place, attempting to stay on a trajectory that she perceives as straight, the participant unwittingly veers in the direction of the induced rotation. When she spins her head to look around the VE, the rapid turning causes substantial vestibular stimulation. Against this background of high vestibular stimulation, an additional vestibular stimulation that would be noticed while standing in place is unnoticeable. Therefore the participant does not notice the increased rotation we inject while she is looking around.

For RWP to be successful, the participant must register and respond to the continuously updated orientation of the VE without recognizing the changes as external in origin. Furthermore, the rotation must not increase the simulator sickness of the participant. Because the technique keeps the visual and vestibular cues consistent, the added rotation should cause participants to change direction, but should be unnoticed. Since simulator sickness is believed to be caused by discrepancies between visual and vestibular cues [15], we believe RWP does not cause an increase in simulator sickness. We carried out a pilot study to test the feasibility of the technique.

4. Study

We explored the viability of Redirected Walking in Place with a user study. Since previous work shows walking-in-place is better than flying [6], we did not re-examine flying or other vehicle-like metaphors. We compared turning automatically with redirection to turning manually with a hand-controller. Participants were asked to carry out a task in a VE. The control group turned in the VE using a hand controller and the experimental group used RWP. Both groups completed the same task in the same VE and both used walking in place to move forward.

44 people were recruited for this pilot experiment from around the UCL campus by advertisement, and were paid £5 upon completion. They were randomly assigned to the control group or the experimental group. Due to loss of data (for equipment failures), the final allocations were 13 people to the control group, and 15 for the RWP (experimental) group.

4.1. Task

The task was to find and read four signs, labelled 'Alarm', 'Halon', 'Practice' and 'Window' in a virtual brick room (fig. 4). Participants were asked to find and read all four signs, then to revisit each in alphabetical order. This task forced the participant to walk about and explore the large virtual room and was specifically designed to involve many

3 Computed as the smallest angle between the participant's torso and the front wall, thus was always in the range -180 to +180.

substantial changes of direction. Before beginning the task, participants were familiarized with the VE equipment and practiced walking in place.

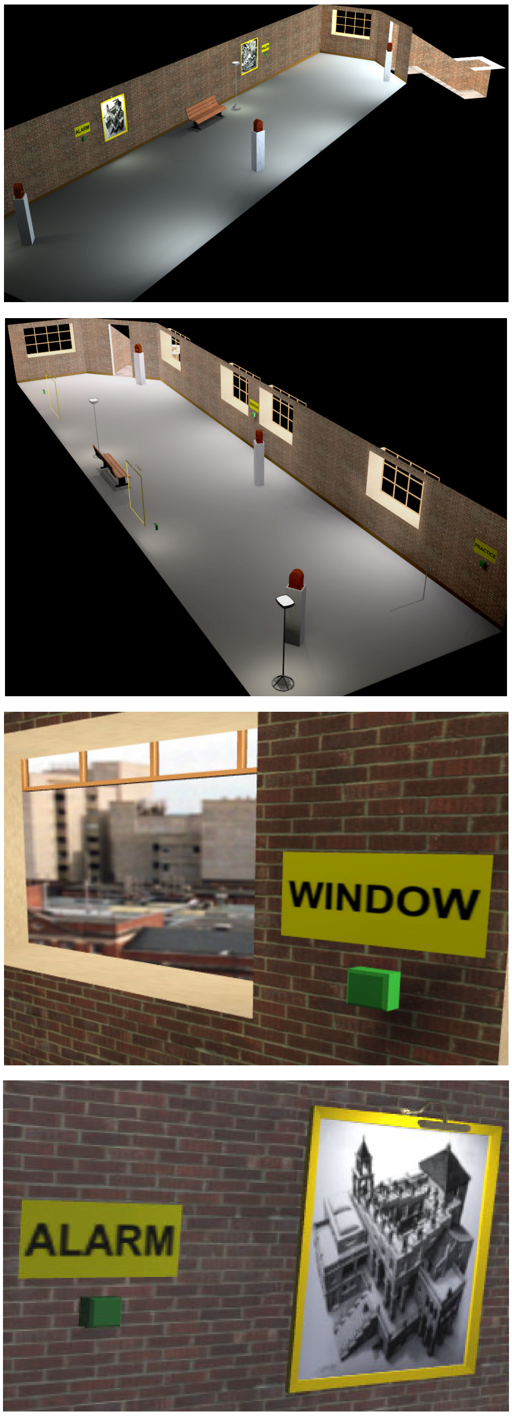

Figure 4: *Several views of the VE used in this study. Two of the four signs are visible in the lower two images.*

4.2 Measures

The overall goal of the experiment was three-fold. The first goal was to test whether the RWP method, as implemented at that time, resulted in a lower frequency of noticing the open back wall than the normal method of CAVE™ movement (as experienced by the control group). The second and related goal was to see whether people in the RWP group actually noticed whether the world was rotating about them. The third and most high level goal was to examine the impact of this on the sense of presence.

Although this was a between-groups study (each participant only experiencing one condition), it was not a matched case-control study. Therefore, we gathered additional information about each participant to use in regression studies of the variation of response variables with the explanatory and independent variables. These 'demographic' variables included gender, status (i.e., whether undergraduate, graduate, academic staff, administration or other), their extent of computer game-playing, and their prior experience with virtual reality. We also used the Simulator Sickness Questionnaire [20] for assessing simulator sickness. Readings were taken from each participant before and after their experimental session.

The experimental variables were as follows:

saw_back_wall - this is a measure of how often[4] during the session the open back wall came within a 40º field of view of the participant. Other similar measures were taken at varying fields-of-view (2º, 20º, 40º, 65º, 90º and 106º) and all were positively correlated. In addition to this objective measure, we included a question that assessed the extent to which people actually noticed whether the room was rotating. In order not to alert participants to this possibility, the question of whether they had noticed the room unexpectedly rotating was embedded amongst a series of similar questions, such as whether they noticed the VE flickering, getting brighter or darker, or changing size.

We also measured the actual amount of head and torso rotation, and how much the participant really walked about in the CAVE™. Previous studies [13] have found that presence is positively correlated with such (appropriate) body movement. In this situation, though, when participants turn their heads or their bodies, the world (ideally without the participant noticing) rotates to compensate. However, if this rotation is noticed, we would expect that this would decrease presence, since it is contradictory to everyday experience. Therefore, there is potentially a complex relationship between saw_back_wall, the amount of head rotation (sdhead) and the amount of torso rotation (sdtorso). In fact, as would be expected, sdhead and sdtorso are almost perfectly correlated ($R^2 = 0.98$) so in subsequent discussion we only use sdhead.

reported presence - this was assessed on six questions in the post-experimental questionnaire, exactly following the format used on several previous occasions [12, 13, 21]. The six questions were:

[4] Computed as the percentage of time while carrying out the task

I had a sense of 'being there' in the brick room
[1. not at all … 7. very much]

There were times during the experience when the brick room was the reality for me
[1. at no time … 7. almost all the time]

The brick room seems to me to be more like
[1. images that I saw … 7. somewhere that I visited]

I had a stronger sense of
[1.being in the lab… 7. being in the brick room]

I think of the brick room as a place in a way similar to other places that I've been today
[1. not at all … 7. very much so]

During the experience I often thought that I was really standing in the brick room...
[1. not very often … 7. very often]

Each was answered on a 1 to 7 scale where a higher score indicates greater reported presence. The overall score for a participant is the number of 'high scores' amongst the six questions, where a high score is taken to mean a score of 6 or 7. Hence the overall score is a count variable (ranging from 0 to 6) and is treated as a binomial response variable in a logistic regression (as in previous analyses).

The major questions of interest therefore were:

(a) How does saw_back_wall vary between the two experimental conditions (in other words, saw_back_wall lower for the RWP condition than for the control condition)?

(b) Does the RWP method produce a greater level of simulator sickness than the control method?

(c) How does presence vary with saw_back_wall? - we would expect that presence should decrease with higher saw_back_wall - the more that people see the open back wall, the lower their sense of presence. If this is the case, then the quest to make the RWP method work is worthwhile.

4.3. Equipment

The CAVE™ used in this experiment was a Trimension ReaCToR™ with four projection surfaces (3 vertical walls and the floor). A SGI Onyx2 with eight R12000 processors and four IR2 graphics pipes generated imagery at 22.5 frames per second. Participants wore Crystal Eyes™ shutter glasses to view stereo imagery. An Intersense IS-900 tracker provided the position and orientation of the participant's head and torso. The IS-900 wand, which is normally held in the participant's hand, was attached to the participant's waist with a hip worn camera bag to track the participant's torso instead of hand. (fig. 5). Participants held a Logitech® wireless computer mouse while performing the task. In the control condition, where the participant turned using the mouse, pushing the right button rotated the VE to the right. Similarly, pushing the left button rotated the VE to the left.

A neural network analysed head motion data from the tracker and determined, in real-time, when the participant was walking in place [6] The latency of this walk-in-place detector (the time lag between the participant starting to walk and the neural net detecting it) was approximately 0.25 to 0.5 seconds.

Figure 5: *The torso tracker (above). A participant wearing the torso tracker and holding the wireless mouse (below).*

5. Results

(a) There is no significant difference in the mean values for saw_back_wall between the two conditions. In the control condition the mean value is 8.4% ± 13.7%, and in the RWP condition it is 11.2% ± 5.1%. In other words, the implementation of RWP used for this pilot experiment did not result in a decreased frequency of looking towards the blank wall. However, the variance for the RWP condition is significantly lower than for the control condition ($p < 0.0005$). Subjectively, the number of times that participants in the RWP condition noticed that the world was unexpectedly rotating was much higher (7/15) than for the control group (1/13). For all the other such variables (VE flickering, changing size, etc.) the results were evenly distributed amongst the two conditions.

(b) There is no significant difference between the conditions regarding simulator sickness. The means of the SSQ scores are 11.8 ± 13.2 and 10.2 ± 8.5.

(c) We examined the relationship between reported presence and saw_back_wall taking into account demographic variables, and the amount of head rotation. This was achieved with presence as a binomial response variable in a logistic regression, as mentioned earlier.

Of the demographic variables only 'status' is significantly related with reported presence. Presence is higher for Masters students and marginally lower for PhD students. The important point about this variable is that we use it to minimize systematic differences between people that may have a bearing on the variation of presence.

These results are consistent with previous work. The more participants rotated their head or torso, the higher the sense of presence (other things being equal). As expected, the more that participants noticed that the room rotated, the lower their reported presence. Also, the more that (objectively) the open back wall came into their (40º) field of view, the lower the sense of presence. Table 1 summarizes the results. The 'coefficient' column shows the parameter estimate for the corresponding variable in the logistic regression analysis, and the 'S.E.' column shows the standard error of the estimate. The χ^2 column shows the chi-squared value for deletion of the corresponding variate from the model. This should be compared with the tabulated 5% value of 3.841 on 1 degree of freedom (d.f.). In other words, no variable can be deleted from the model without significantly worsening the overall fit.

Variable	Coefficient	S.E.	χ^2 (1 d.f.)
Rotate	-1.6	0.68	6.4
saw_back_wall	-0.17	0.061	8.6
sdhead	0.029	0.0093	11.1

Table 1: *Logistic Regression Results (n = 28)*

Figure 6: *The path taken by participant SB5 in the VE while performing the task.*

6. Comparison to other Techniques

In addition to flying [1], and redirected walking in place, there are several other techniques that allow participants to explore large VEs in open backed CAVEs™. Among these are unicycles [22] and bicycles [2], single and multi-axis treadmills [2 3 4 5 23], and leaning gestures [8 9].

Each of these methods has its own advantages and disadvantages. Real walking provides multi-sensory cues: visual, vestibular and proprioceptive [24]. Treadmills provide realistic proprioceptive cues of walking. Single axis treadmills are disorienting while the participant is turning in the VE [2] while multi axis treadmills are loud and mechanically complex. RWP, on the other hand, requires only hardware common to CAVE™ systems. Leaning gestures are mechanically simple and do provide some vestibular cues, but do not provide the proprioceptive cues of walking.

Redirected Walking in place is most similar to La Viola's Auto-rotation technique. Both RWP and Auto-rotation allow the participant to turn with their body and respond by automatically rotating the VE to keep the participant from seeing the open back wall. Both techniques also free the participant's hands. Auto-rotation magnifies the participant's orientation so they can see in all virtual directions. For example, if the participant is standing in the centre of the CAVE, the 270º physical field of view that is covered by the CAVE walls are mapped to a 360º virtual field of view.

Despite the similarities, RWP and auto-rotation have different objectives. RWP walking aims to rotate the VE in a manner that is not noticeable and does not increase simulator sickness, by accounting for the visual and vestibular responses to the rotation. Also, RWP causes a participant to unwittingly turn towards the front wall, even if they are not actively turning in the VE. Auto-rotation aims to improve ease of use, and is used in conjunction with leaning to move in the VE. On the other hand, RWP aims to improve presence and naturalness by mimicking the way a participant would move through the real world - it is used with walking-in-place. If a participant becomes tired by walking 5 km in the real world, she will also become tired when she moves 5 km in the VE with walking-in-place, but not with the leaning technique. We do not know of any studies showing if Auto-rotation is noticeable or how it affects presence or simulator sickness. In this pilot experiment, we did not compare the Auto-rotation to RWP, though it would have been interesting to do so.

7. Conclusions

Some participants find it cumbersome and distracting to turn with a joystick or hand controller. During the post-session interview, one participant (#SC7, in the control group) commented about how he used the hand controller:

> *SC7* – 'when I got stuck. When it would take too much turning around. I think that it was very unrealistic. Um – a very still traversing'.
>
> *Experimenter* – 'So you preferred to turn with your body unless you got stuck'?
>
> *SC7* – 'Oh ya – uh huh'

RWP frees the participant from needing a hand controller for movement in the VE.

Although RWP, as implemented in the pilot study, does not reduce the fraction of time the participant sees the open back wall of the CAVE™, it does reduce the variance. Its employment does not result in any change in simulator sickness. The quest to reduce the number of times that participants notice the blank wall is a worthy effort, since the evidence suggests that it would result in an increased sense of reported presence. Although it did not, as implemented in the study, meet our goals across all participants, we do have subjective evidence that it worked for some of them. One participant (#SB9, in the RWP group), when asked how much she saw the open back wall, reported:

> 'No – I didn't think I noticed it all, I don't think. I don't know… I don't know if I ever turned around that far. But I supposed I must have because I was

walking in all sort of directions, but I don't remember seeing it – no'

Redirected Walking has promise and merits further development.

Acknowledgements

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Appendix A – Details of Rotation Algorithm

The rendering frame rate during the experiment was 22.5 Hz. For each frame, the rotation rate was computed using the following pseudo code:

```
rate_still = 0.145
rate_slew = 0.45 * abs(head_angular_velocity)
rate_walking = output_from_walking_neural_net
               * 0.38
overall_rate = max_of(rate_still,
               rate_slew,
               rate_walking)
dir_coeff = sin(theta * 2.0)
deg_to_rotate_VE_this_frame = over_rate *
                              dir_coeff
```

Angular velocity is measured in degrees per frame. Theta is the angle between the participant's torso orientation and the front wall (fig. 4). The constants above were not optimal (based on the results of this pilot experiment). We include them only to allow readers to duplicate our results.

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