Recalibration of Rotational Locomotion in Immersive Virtual Environments*

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Abstract

People recalibrate, or adjust, their actions as environmental conditions change. For example, people can easily recalibrate to walking outside on a windy day. Locomotive recalibration, such as walking or turning, has already been investigated in several real world experiments. However, there has been little research of locomotive recalibration in immersive virtual environments (IVEs). This work describes a series of experiments that were created to determine if and how people recalibrate to different rates of rotation in IVEs. The experiments were designed after real world experiments conducted by Pick, Rieser, Wagner and Garing [1999]. The results of our experiments show that people do recalibrate to virtual environments in a way that is similar to the way they recalibrate in the real world. In addition, these results verify that IVEs can be an alternative way to conduct traditional real world perception experiments.

CR Categories: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

Keywords: immersive virtual environment, perception, rotation, recalibration

1 Introduction

Unlike the real environments used in traditional psychology experiments, virtual worlds have the potential to provide high amounts of both experimental control and ecological validity [Loomis et al. 1999]. However, imperfect graphics and limited frame rates can introduce significant problems when immersive virtual environment (IVE) technology is used for perception experiments. We are interested in comparing the results of IVE recalibration experiments to the results of real world recalibration experiments [Pick, Jr. et al. 1999; Rieser et al. 1995]. Recent research has investigated the recalibration of translatory human locomotion in IVEs [Fox and Durgin 2003; Mohler et al. 2004] but little research has focused on the recalibration of rotation in IVEs.

Real world experiments conducted by Pick et al. [1999] used a turntable to create a discrepancy between the biomechanical stepping rate and the turning rate of subjects. In these experiments, a pre-test, recalibration phase and a post-test were used to measure the amount of recalibration. The pre- and post-tests were identical and involved having the subjects note the direction they were facing in a room, close their eyes and rotate in place until they thought that they had turned in a complete circle. During the recalibration phase, subjects turned in place on a turntable mechanism that allowed them to see the room rotating at a different rate than their legs were moving. In one particular experiment, the subjects stepped at a rate of 10 rpm while seeing the environment rotating at 5 rpm. In these conditions, we say that the subject was experiencing a situation that was visually twice as slow or biomechanically twice as fast. Our experiments were closely modeled after these turntable experiments but we used a stereo head mounted display (HMD) to display a virtual room that subjects would view in the pre-test, recalibration phase and post-test.

Despite many similarities between our IVE experiments and the turntable experiments they were modeled after, there are several significant differences. The turntable system required the subjects to rotate at a constant, mechanically set rate. Our IVE system allowed subjects to rotate naturally while the computer multiplied the natural rotation rate by a factor to determine the virtual world rotation rate. This allowed subjects to repeatedly rotate, stop and rotate again. This limited an adaptation effect noted in the results of the experiments by Pick et al. [1999]. In one of their experiments, subjects rotated continuously in one direction in a visually and biomechanically matched condition. The continuous stepping movement in that direction caused subjects to overshoot in a post-test in the same direction of rotation by 34 degrees compared to the pre-test. When the pre- and post-tests were in the opposite direction of the turning in the recalibration phase, they turned 30 degrees less. Secondly, the vestibular information matched the visual information in the real world experiments. However, the vestibular information in our experiments matched the biomechanical rotation rate. Another significant difference in our experiments is that subjects were not physically prevented from translating to a different position in the environment. Although they were told to try to rotate in place throughout the experiment, the virtual environment accurately displayed viewpoint translation. Lastly, a turntable system does not correctly recalibrate the rotation of the subjects' heads. For example, if a subject turned their head while on a turntable in a visually twice as fast condition, the rate of their head rotation is simply added to the rate of rotation of their body. This additional head rotation should instead be first multiplied by two before it is added to the rate of body rotation. The IVE easily solves this problem because the tracking system measures the orientation directly from the head of each subject.

2 Experiments

2.1 Design

The subjects for all experiments were Augsburg College students, faculty and staff. Prior to each experiment, subjects put on an HMD and were assisted in walking around the lab with their eyes closed. The HMD had a piece of cloth attached to it to prevent subjects

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from seeing the real room if they opened their eyes. The lights were turned off during the experiment to make the subjects focus on the virtual world. Although blind walking prior to the experiments might not have been necessary, it ensured that people were comfortable with not being able to see if they were near a wall or other obstacle. During the blind walking task, subjects were blindfolded and instructed to walk straight ahead. When they approached a wall, the experimenter turned them in a random direction and they resumed walking forward. After approximately five minutes of blind walking, the subjects were brought to the center of the lab and were told to only rotate in place for the remainder of the experiment. In general, they were able to stay in the center of the room. Some subjects occasionally needed to be guided back to the center of the room after they drifted near the edge of the tracked space. They wore headphones that played static to prevent them from using audible landmarks to determine how far they were rotating. They could also hear the directions given by the experimenter through the headphones.

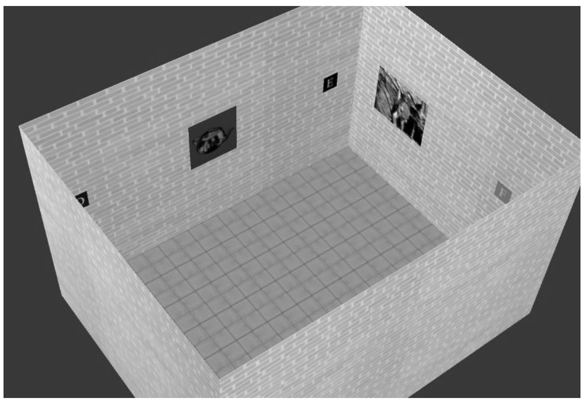

Figure 1: Aerial view of the virtual room (ceiling removed)

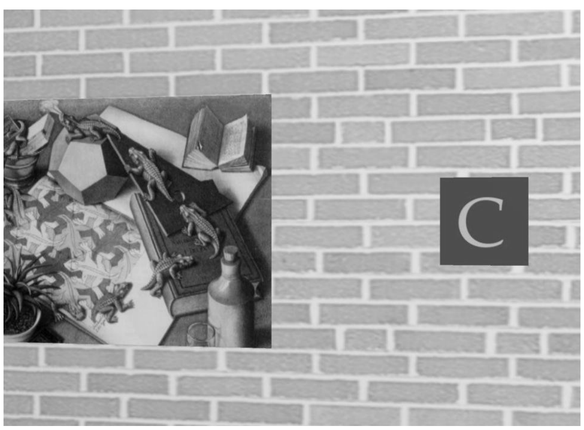

Figure 2: A subject's view of the virtual room

Subjects viewed the virtual environment by wearing a Kaiser Electo-Optics Proview XL50 HMD that provided a 40x30 degree field of view. It had two 1024x768 pixel displays with a 24-bit color depth. A workstation with an nVIDIA GeForce Ti 4200 graphics card simultaneously rendered the left and right eyes at a rate ≥ 30 frames per second during the experiments. An InterSense IS-600 Mark 2 motion tracker was used to determine the position and orientation of the HMD within a three by five meter tracked space.

The subjects were shown a rectangular shaped virtual room that was approximately the same size as the lab (Figure 1). The room had a gray brick texture on the walls to increase the effect of visual flow during rotation. The floor and ceiling were also textured. There were six posters with letters on them and four more posters used to break up the brick texture. The six lettered posters each had a unique color and a unique letter (A–F) on them. Figure 2 shows how the subjects saw the world in the HMD taking into account the HMD's field of view.

The experiment consisted of a pre-test, recalibration phase and a post-test. In the pre- and post-tests, the subjects were shown a virtual green poster with a 'C' on it. They were told to view the poster until they had a good idea where the poster was in the virtual room. Next, the subjects closed their eyes, the HMD graphics were turned off and they were told to turn to their left or right (depending on the particular experiment) in a complete circle until they thought they were facing the exact same direction that they were facing when they were viewing the poster (a 360 degree rotation). A yaw (left/right angle) measurement was made by the tracking system immediately before the subjects started to turn and immediately after the subjects stopped their turn. After completing the turn, the subjects were told to turn back in the opposite direction of their original turn. This extra turn was also done with the graphics turned off to prevent the subjects from seeing how accurate their 360 degree turn was. They were repeatedly told not to use any counting techniques to determine how far they were turning.

The angles recorded in the pre- and post-tests were used to compute the amount of rotation the subjects made. In each variation of the experiment, half of the subjects were told to turn to the right and the other half were told to turn to the left in the pre- and post-tests.

After the pre-test, the subjects were given a series of thirty instructions. Each instruction told the subjects to turn left or right with eyes open until they saw a particular lettered poster in the virtual room. For example, the first instruction was "Turn right until you see the black poster with an E on it." The subjects were given the next instruction after they had completed the turn for the previous one. They were allowed to complete the series of instructions as slowly or as quickly as they desired. The same list of instructions was used for each variation of the experiment. The instructions were designed so that they would turn the same amount to their left as they did to their right with respect to the virtual environment. The subjects were not required to turn their whole body when they followed the instructions, but the instructions were designed so that subjects would not be able to easily view the posters without moving their feet. It took approximately ten minutes for a subject to complete this recalibration phase.

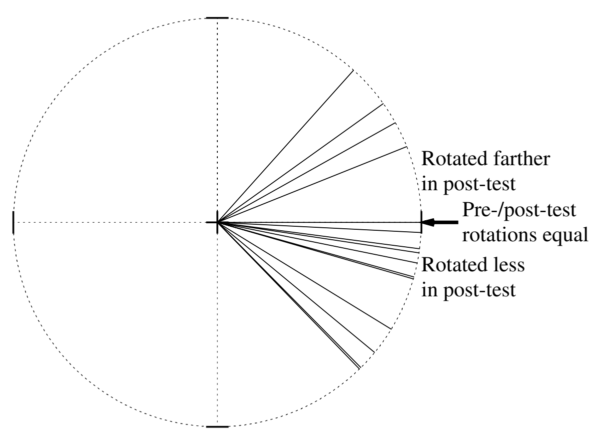

Figure 3: Matched visual and biomechanical speeds. Average: 5.7° less rotation in post-test compared to pre-test.

2.2 Experiment I: Control

The first experiment was designed to determine if our virtual reality system had some inherent characteristics that caused subjects to recalibrate. When each of fifteen subjects rotated inside the virtual room, their visual rotation rate matched their biomechanical rotation rate. In other words, the subjects saw their view of the virtual room change in exactly the same way that it does when they rotate inside real rooms.

Figure 3 shows the results of this control experiment. Each subject is represented as a solid line in the figure. The difference between the amount of rotation in the pre-test and the amount of rotation in the post-test determines the angles of the solid lines. The results indicate that there are no significant characteristics of our virtual reality system that cause subjects to recalibrate their rotation. The amount of variation between subjects shown in Figure 3 is similar to the variation in all of the experiments we conducted. Furthermore, this result shows that by having subjects turn in both directions during the recalibration phase we eliminated the sensory adaption-like mechanism discussed by Pick et al. [1999].

2.3 Experiment II: Recalibration of Yaw

Experiment II was designed to determine how people recalibrate to environments where the rate of yaw rotation is visually faster or slower. Each of the fifteen subjects that participated in Experiment I returned on a later date to participate in Experiment II. The recalibration phase for half of these subjects was visually twice as fast as their biomechanical rotation rate. For the other half, it was visually twice as slow. By rotating the entire virtual room around the viewpoint of the subject, we were able to cause subjects to see the virtual room rotating at a rate that was different than the biomechanical rotation rate.

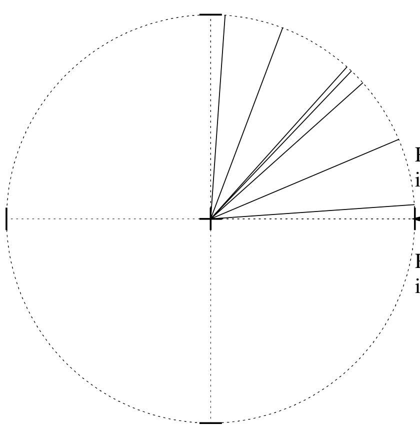

Figure 4: Visually slower by factor of two in both directions. Average: 45.3° more rotation in post-test compared to pre-test.

The results from the visually slower and faster conditions are shown in Figures 4 and 5 respectively. In both conditions there was an average recalibration of approximately 45 degrees. If the subjects had been completely recalibrated to the visually slower and faster rates, we would expect this average to be near 180 degrees.

Although it is difficult to directly compare the results of these experiments to those of Pick because of the differences discussed in the Introduction, some parallels do exist. In their Experiment 5, subjects paid particular attention to posters on the walls during rotation similar to the way subjects were told to find posters in our

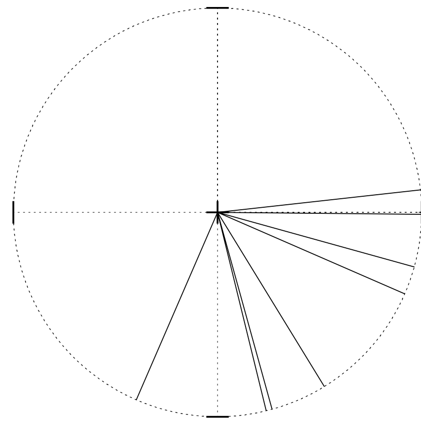

Figure 5: Visually faster by factor of two in both directions. Average: 44.7° less rotation in post-test compared to pre-test.

experiments. In the matched speed condition, their subjects overshot by eight degrees. They overshot by 79 degrees in the visually slower condition and undershot by 32 degrees in the visually faster condition. Thus, despite the experimental differences, it appears that the magnitude and the amount of variation in the real world results are similar to the results of Experiments I and II described here.

2.4 Experiment III: Directionally Dependent Recalibration of Yaw

Since the results of Experiment II showed that it was possible to recalibrate subjects to different rates of left/right rotation, Experiment III was designed to determine if people were able to recalibrate differently depending on the direction that they turned.

Thirty-one subjects participated in this experiment. All of these subjects had not participated in previous rotational recalibration experiments. The subjects were divided into two groups. The recalibration phase for sixteen of these subjects was visually twice as fast for left rotation but visually and biomechanically matched for right rotation. For the other subjects, it was visually twice as fast for left turns but visually twice as slow for right turns.

Figure 6 compares the results of this experiment to the results from Experiments I and II. In both variations of this experiment, left rotation was always visually faster by a factor of two. If left rotational recalibration is independent of the amount of right rotational recalibration, the amount of recalibration for left rotation should stay near 45 degrees. Instead, the amount of left recalibration was reduced when the right rotation was visually and biomechanically matched. In the faster left turn and slower right turn condition, the amount of recalibration in the right turn post-tests was dramatically reduced compared to 45 degrees of recalibration found in the visually slower rates in both directions. These results strongly indicate that the left and right rotation cannot be independently recalibrated.

However, the visually faster left rotation did not impact the visually/biomechanically matched right rotation. Furthermore, the visually faster left turns, when combined with the visually/biomechanically matched right turns, led to less recalibration than when they were combined with the visually slower right turns. These results indicate that there is an indirect relationship between left and right rotation that should be examined more deeply. An understanding of this particular connection has the potential to provide

Exp.	Visual condition		Amount of recalibration	
	Left	*Right*	*Left*	*Right*
I	Matched	Matched	-5.7	
II	2x faster	2x faster	-44.7	
II	2x slower	2x slower	+45.3	
III	2x faster	Matched	-26.4	-4.0
III	2x faster	2x slower	-37.2	+14.3

Figure 6: Summary of results. Average difference between post- and pre-tests are shown in degrees. Negative numbers are used when subjects turned less in post-test compared to pre-test. When the visual condition was the same for both left and right rotation, the results from left and right turn pre- and post-tests are combined.

insights into the psychological mechanisms people use to recalibrate their locomotion. Future work might include repeating these experiments with more subjects to try to determine the amount of recalibration more accurately.

2.5 Additional Results

When the results of all of the pre-tests are combined, subjects turned 15.5 degrees short of a full circle on average. This result could be attributed to a psychological effect of people not wanting to turn past a complete circle and then having to turn back after they realize that they turned too far. However, this result could also be caused by the subjects wearing the two pound HMD throughout the experiment [Willemsen et al. 2004]. It is important to note that this particular result has no direct impact on the results from Experiments I–III because we measured the difference between the amount of rotation between the pre- and post-tests.

After each experiment, subjects were asked if they felt physical sensations such as dizziness or nausea during the experiment. No subjects reported any significant sensations but 37 percent reported that they experienced slight dizziness or eye strain. Because of the high amount of rotation and mismatched biomechanical/visual rotation rates that were used in these experiments, it was expected that a significant minority of subjects would experience small amounts of dizziness and eye strain.

After Experiments II and III, subjects were all verbally asked if they noticed anything strange about how they were rotating in the virtual room. The majority of people answered that they thought they were rotating in the virtual room just like they would have in a real room. Approximately 20 percent explained that they thought that the posters might have been moving around the room—a side effect of the mismatched virtual and biomechanical rotation rates. Another 15 percent of the subjects realized that the virtual room moved slower or faster than it should have. Even in Experiment III, where the difference in the rate of left and right rotation was a factor of four, only 15 percent of the subjects were able to recognize exactly what was happening during the recalibration phase. When the subjects were completely done with the experiment they were told what was happening during the recalibration phase. Even if the subjects had said that they saw nothing strange during the recalibration phase, nearly every subject immediately realized that they did notice the virtual world moving strangely after the rotation effect was explained to them. This result indicates that subjects were able to perceive the difference in rotation but that they were comfortable with becoming partially immersed into the IVE and trusted that the visual information provided in the HMD was accurate.

Since it is difficult for the human perceptual system to notice visually and biomechanically mismatched rotation rates, we can improve the usefulness of IVEs by exploiting human perception. Razzaque et al. [2001] have shown that it is possible to dynamically change the visual rate of rotation to encourage subjects to stay within a finite tracked real world space while the subjects feel as if they are in an infinite virtual space. In their experiments, subjects wore an HMD and walked around in a tracked space. The virtual world forced subjects to frequently rotate. The visual rate of rotation was increased or decreased in a way that caused subjects to stay within the tracked space. It might be possible to apply our findings on rotational recalibration in a way that produces a similar result without many subjects noticing the mismatched biomechanical and visual rotation rates.

3 Summary

These experiments show that people recalibrate in IVEs in a way that is qualitatively similar to how people recalibrate in the real world. However, a direct comparison between our experiments and those conducted by Pick will require additional research because of the experimental differences discussed in the Introduction. This research also shows that more work needs to be done to fully understand the relationship between the recalibration of rotation in different directions, particularly addressing how rotational recalibration in one direction affects the rotational recalibration in the other direction. Additional ideas for future research include implementing an IVE that allows people to be in an environment that visually rotates in the opposite direction of biomechanical rotation as noted at the end of the discussion of the turntable experiments. We are also looking at conducting experiments to determine if a recalibration in pitch (up/down rotation) will cause a recalibration in yaw.

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