Rotational Recalibration 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 [4]. 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.

Background

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 [2]. However, there are significant problems with using current immersive virtual environment (IVE) technology for perception experiments. Imperfect displays, models and rendering coupled with slow frame rates and lags in head tracking introduce the potential for the results of an IVE experiment to differ from the results of a corresponding real world experiment. We are interested in comparing the results of IVE recalibration experiments to the results of real world recalibration experiments conducted by Pick, Rieser and others [4, 5]. Recent research has investigated the recalibration of translatory human locomotion in IVEs [1, 3] but little research has focused on the recalibration of rotation in IVEs.

Real world experiments conducted by Pick et al. [4] 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

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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 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. [4] where visually and biomechanically matched conditions cause the subjects to adapt to the movement and perform differently in the post-test compared to the pre-test. 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 properly displayed the subject's location if the subjects did translate their viewpoint. 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 already measures the orientation directly from the head of each subject.

Experiments

Design

The subjects for all experiments were Augsburg College students, faculty and staff. Prior to each experiment, subjects put on a head mounted display 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 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 the blind walking might not have been necessary for the experiment, it ensured that people were comfortable with not being able to see if they were near a wall or other obstacle. 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 occasionally needed to be guided back to the center of the room after they drifted near a wall. 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.

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) until they thought they were facing the exact same direction that they were facing when they were viewing the poster. 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 always turned to the right and the other half turned to the left during the pre- and post-tests. Unless otherwise noted, the results were mirrored so that both types of pre- and post-tests are represented in a single figure.

After the pre-test, the subjects were given a series of thirty instructions. Each instruction told the subjects to turn left or right until they saw a certain poster in the virtual room. There were five posters in the rectangular shaped room. Each poster had a unique color and a unique letter (A–E) on it. 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 subjects 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 the recalibration phase.

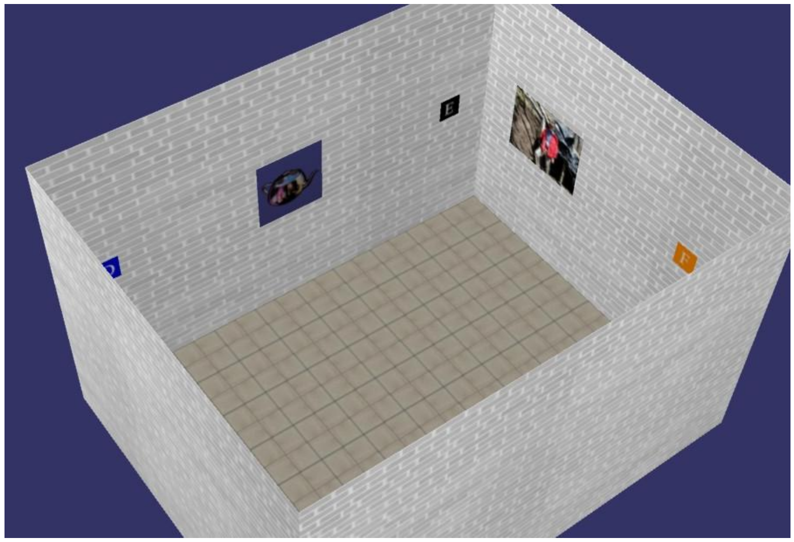


Figure 1: Aerial view of the virtual room (ceiling removed)

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

The virtual room used for the pre-test, recalibration phase and post-test is shown in Figure 1. The room had a gray brick texture on the walls to increase the effect of visual flow during rotation. The floor had a realistic tile texture on it and the ceiling had a subtle texture on it. In addition to the five posters in the virtual room that the subjects were told to look at, there were several other posters on the walls to break up the brick texture. Figure 2 shows how the subjects saw the world in the HMD taking into account the HMD's field of view.

Experiment I: Control

Method

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.

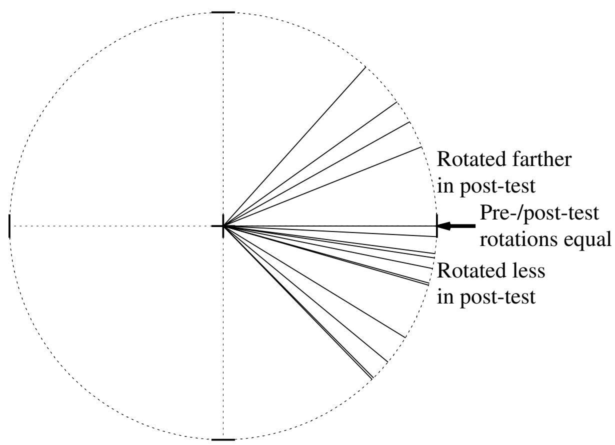


Figure 3: Matched visual and biomechanical speeds (average: 5.7° or 2% less rotation in post-test compared to pre-test).

Results

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.

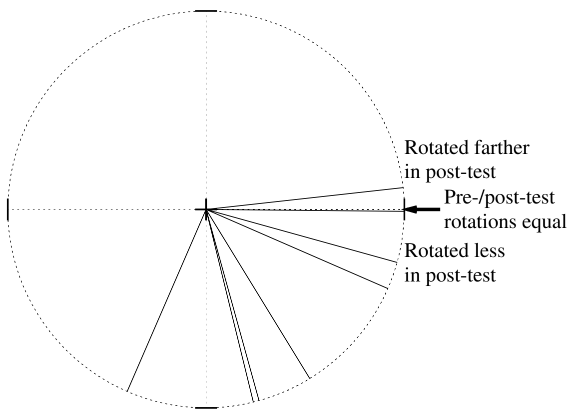
Experiment II: Horizontal Recalibration

Method

Experiment II was designed to determine how people recalibrate to environments where the rate of yaw (left/right) 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.

Results

The results, shown in Figure 4, indicate that subjects were able to recalibrate to the increased or decreased visual rotation rate. In the visually faster condition, nearly all of the subjects turned less in their post-test than they did in their pre-test. In the visually slower condition, every subject turned farther in their post-test than they did in their pre-test. In both conditions there was an average recalibration of 45 degrees or 13 percent. If the subjects had been completely recalibrated to the visually slower and faster rates, we would expect this average to be near 180 degrees.



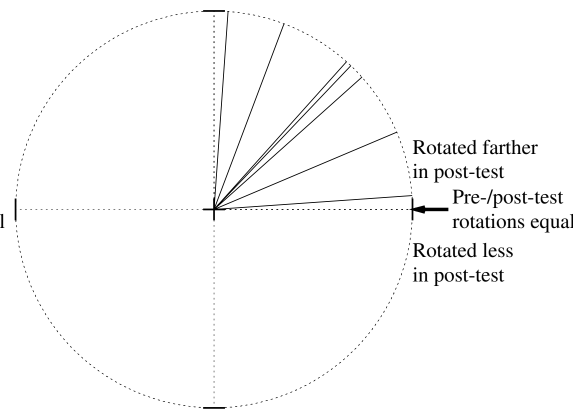


Figure 4: *Left:* Visually faster by factor of two in both directions (average: 44.7° or 13% less rotation in post-test compared to pre-test). *Right:* Visually slower by factor of two in both directions (average: 45.3° or 13% more rotation in post-test compared to pre-test).

This experiment shows that our virtual environment caused people to recalibrate their rotation in a way that corresponds to the findings of Pick et al. [4] in the real world. The amount of recalibration found in this experiment is similar to the amount of translatory recalibration found by Mohler et al. [3] in a treadmill-like IVE. In these experiments, subjects walked in a virtual environment on a treadmill-like locomotive interface to an IVE. A blind walking task to a previously seen target was used as a pre- and post-test. When the virtual world moved at a rate twice as fast as the biomechanical walking rate, they found subjects undershot the previously seen target by 5 percent relative to the pre-test. Likewise, when the virtual environment was visually half as fast, subjects overshot the targets by 9 percent. In our corresponding rotational recalibration experiments, subjects rotated either 13 percent too little or too far in the post-test of the visually faster or slower conditions compared to the pre-test. If people use the same process to recalibrate to translatory locomotion as they do to rotational locomotion, we might expect that the magnitudes of recalibration would be similar for these two actions. However, the difference in magnitude between our experiments and those by Mohler et al. indicate that there might be separate psychological processes that are used for translatory and rotational recalibration. The difference could also be explained by differences in the experimental process of the two experiments.

Experiment III: Directionally Dependent Recalibration

Method

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.

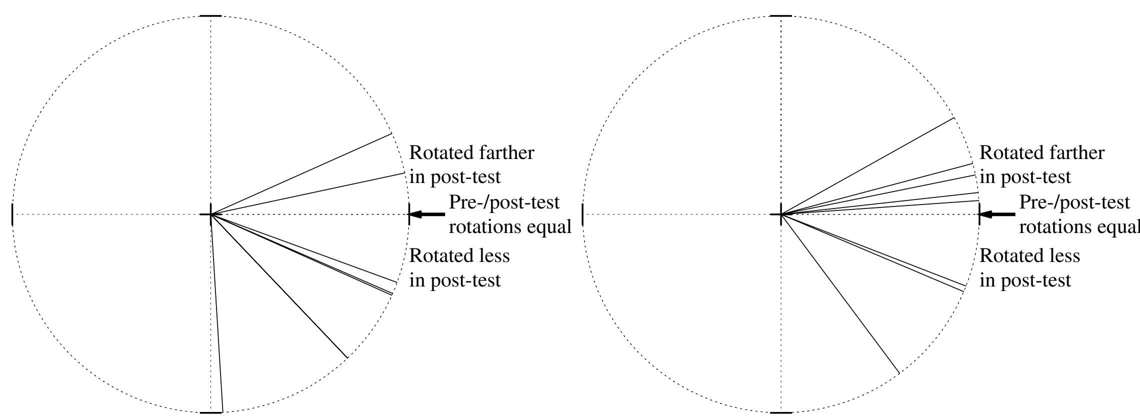


Figure 5: *Left:* Visually faster by factor of two when turning left; matched biomechanical and visual speeds when turning right; left turns in pre-/post-tests (average: 26.4° or 7% less rotation in post-test compared to pre-test). *Right:* Same as left figure except right turns on pre-/post-tests (average: 4.0° or 1% less rotation in post-test compared to pre-test).

Results

Figures 5 and 6 show the results of these experiments. As noted earlier, all of the experiments described in this paper had half of each group of subjects turning left

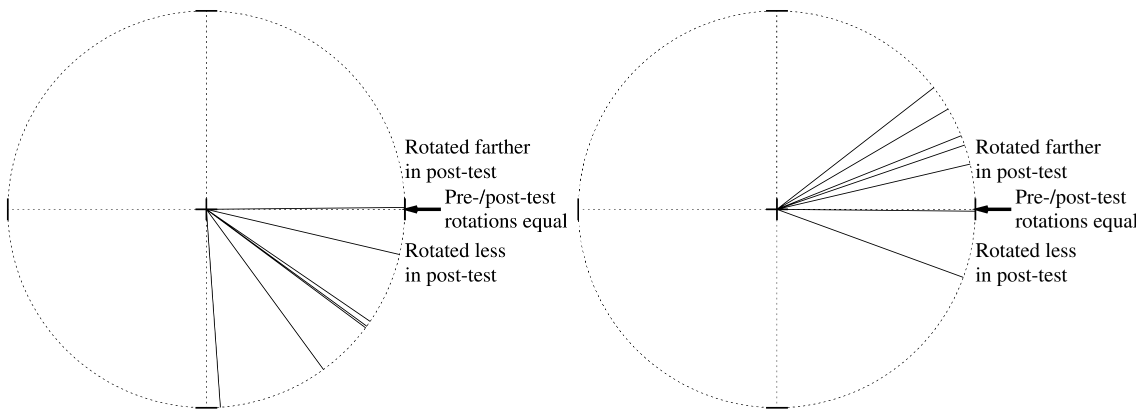


Figure 6: *Left:* Visually faster by factor of two when turning left; visually slower by factor of two when turning right; left turns in pre-/post-tests (average: 37.2° or 10% less rotation in post-test compared to pre-test). *Right:* Same as left figure except right turns on pre-/post-tests (average: 14.3° or 4% more rotation in post-test compared to pre-test).

in the pre- and post-test and the other half turning right. The left sides of these figures show the results for the subjects that turned left during the pre- and post-tests. Likewise, the right sides of these figures show the results for the subjects that turned right.

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 graphs on the left sides of Figures 5 and 6 would be similar. Instead, the amount of left recalibration was reduced when the right rotation was visually and biomechanically matched.

In the case where subjects turned right in the pre- and post-tests, there was no right rotational recalibration when the right rotation was biomechanically and visually matched (Figure 5, right side). When the right rotation was visually slower, subjects did rotate 14 degrees farther in the post-test than in the pre-test (Figure 6, right side). However, Experiment II indicates that if the recalibration in left rotation had no effect on the amount of right rotation, we should expect that subjects should rotate approximately 45 degrees too far.

These two particular results of Experiment III indicate that people do not always recalibrate left and right rotation independently. Further experiments are needed to verify that there is a link between rotational recalibration in different directions and to determine the nature of this link. An understanding of this particular link has the potential to provide insights into the psychological mechanisms people use to recalibrate their locomotion.

Additional Results

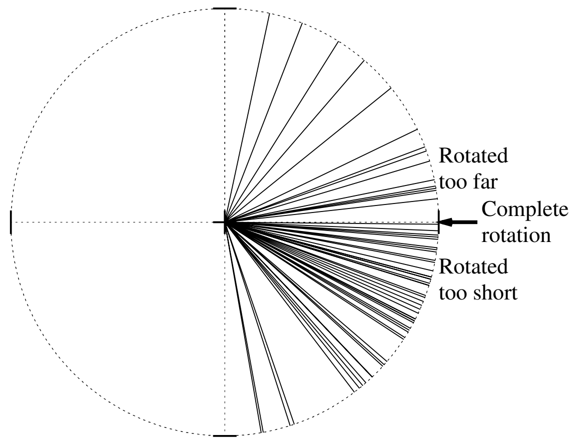


Figure 7: Results of all pre-tests (average: 15.5° or 4% short)

When the results of all of the pre-tests are combined into one graph (Figure 7), it is clear that the subjects generally turned too little when they were told to turn in a complete circle. 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.

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 the different rotation factors 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 were able to recognize 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 exactly what was happening during the recalibration phase. Even if the subjects had just 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.

Implementation

Hardware

Subjects viewed the virtual environment by wearing a Kaiser Electro-Optics ProView XL50 head mounted display (HMD). The HMD provided a 30 degree vertical and 40 degree horizontal field of view. The two 1024x768 pixel displays in the HMD had a 60Hz refresh rate and a 24-bit color depth.

An InterSense IS-600 Mark 2 motion tracker was used to determine the position and orientation of the HMD. The tracking system covered a five by three meter area. The lab containing the tracker system was slightly larger than the area used by the tracker. The tracker communicated with the workstation via a serial cable.

All of the experiments were conducted with a Compaq workstation with a 1.4GHz Pentium 4 processor and 512MB of RAM running Debian GNU/Linux. An nVIDIA GeForce Ti 4200 graphics card with 128MB or RAM rendered the graphics. The dual video outputs on this card simultaneously rendered the left and right eyes.

Software

OpenSceneGraph, an open source software package, was used to create the program to display the 3D graphics. OpenSceneGraph is a set of C++ libraries that wrap around OpenGL to simplify the programming of 3D environments.

The unique part of the graphics software for these experiments is that the rate of rotation in the virtual world is computed by multiplying the rate of real world rotation by a factor. There are two obvious ways to write a program to simulate this affect. First, one could simply take every change in the user's yaw (left/right rotation) and multiply it by a factor to compute the change in yaw in the virtual world. However, this implementation would have accumulated rounding errors due to the continuous addition of small numbers together to compute the virtual yaw. For example, if the biomechanical stepping rate and the visual rotation rate were matched, the virtual room and the real room should stay lined up. If the program were implemented this way, the real and virtual rooms would eventually drift away from each other due to rounding errors. The accumulating error made this approach unusable for the experiments.

Another way to approach the problem would be to record the real world and virtual world angles when the program was started. If the subject started to turn left, the new real world angle would be measured and compared to the real world angle that was recorded when the program started. The change in real world angle would be multiplied by the rotational recalibration factor and then added to the recorded virtual world starting angle. Whenever the subject changed the direction of rotation, the real and virtual angles would again be recorded. All of the rotation in the new direction of rotation would be measured relative to the previously recorded real angle and the virtual angle could be computed from the previously recorded virtual angle. This approach is slightly more complicated to implement, but it keeps the error down to a minimum.

One subtle, but important, side effect of the differing rates of biomechanical and visual motion is that the direction of translation must also be considered. If we changed the rate of visual rotation by simply adjusting the orientation of the camera in the virtual environment, translation in the environment would then be incorrect. For instance, consider an IVE that visually rotates twice as fast as the biomechanical rate of rotation. If the subject started facing a real north wall and a virtual north wall, consider what would happen if the subject turned 90 degrees to the right in the real room to face the real east wall (180 degrees right in the virtual room to face the virtual south wall). When the subject would walk or lean forward in this situation, the subject would be moving toward the real east wall. In the virtual environment, the subject would see themselves moving toward the virtual east wall even though they are facing the virtual south wall. An easy way to solve this problem is to rotate the entire virtual room around the subject's eye-point when they rotate to create different rates of visual rotation. In this case, the camera's rotation in the virtual environment would match the movement of the subject in the real world. However, the entire virtual room would rotate around the subject to produce the recalibration effect. When the subject now looks at the north wall and turns 90 degrees to the right in the real room in a visually twice as condition, the virtual south wall will move around subject 90 degrees to the left. If the subject were to move forward facing the real world east wall and the virtual world south wall, the walls would 'match' and the movement of the camera in the virtual world would be in the correct direction. As previously stated, subjects were told during the experiments to only rotate in place. However, we wanted to make sure that any small amounts of translation or head movements by the subjects would be displayed correctly in the HMD.

Summary

In general, these experiments show that it is possible to model perception experiments in an IVE after experiments conducted in the real world. People appear to recalibrate to rotation IVEs in a way that is closely related to the way they recalibrate in the real world. In addition, the IVE allowed us to control what subjects saw in a way that is not easily possible in the real world.

This research also shows that more work needs to be done to fully understand the relationship between the recalibration of different rotations. Possible areas of future work include a closer examination of how rotational recalibration in one direction affects the rotational recalibration in the other direction. This includes doing more experiments similar to Experiment III with a wider variety of different visually slower and faster conditions for left and right rotation.

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 by Pick et al. [4]. Furthermore, we are looking at conducting experiments to determine if a recalibration in pitch (up/down rotation) will cause a recalibration in yaw (left/right rotation).

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