

Recalibration of Rotational Locomotion in Immersive Virtual Environments

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This work uses an immersive virtual environment (IVE) to examine how people maintain a calibration between biomechanical and visual information for rotational self-motion. First, we show that no rotational recalibration occurs when visual and biomechanical rates of rotation are matched. Next, we demonstrate that mismatched physical and visual rotation rates cause rotational recalibration. Although previous work has shown that rotational locomotion can be recalibrated in real environments, this work extends the finding to virtual environments. We further show that people do not completely recalibrate left and right rotations independently when different visual-biomechanical discrepancies are used for left and right rotations during a recalibration phase. Finally, since the majority of participants did not notice mismatched physical and visual rotation rates, we discuss the implications of using such mismatches to enable IVE users to explore a virtual space larger than the physical space they are in.

Categories and Subject Descriptors: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—*Virtual reality*

General Terms: Experimentation, Human Factors

Additional Key Words and Phrases: perception, recalibration, rotation, virtual environments

1. INTRODUCTION

Perception is closely tied to action in everyday experiences. For example, as an observer walks through an environment, there is a corresponding change in perception of visual motion of the environment. This perception-action coupling has been shown to recalibrate, given systematic variation in the relation between motor, visual, vestibular, or other information for the perception of self-motion. Recalibration is used as a term to describe the changing relationship between perception and action whereas the term adaptation describes a general mechanism of change over time. The mechanism of perception-action recalibration is useful to real-world behavior as it allows people to compensate for changing environmental circumstances. For example, people can quickly adjust the way they walk when they exit a building

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into a windy outdoor environment. Immersive virtual environments (IVEs) provide a convenient platform to investigate perception-action coupling and potential recalibration of actions because they provide large amount of experimental control and complete control over the visual information seen by participants [Loomis et al. 1999].

Several studies have demonstrated that translational locomotion can be recalibrated in real [Rieser et al. 1995] and virtual [Withagen and Michaels 2002; Durgin et al. 2002; Mohler et al. 2007] environments when the visual rate of movement is slower or faster than the physical stepping rate. It has also been demonstrated that rotational locomotion can be recalibrated in a similar manner in real environments [Rieser et al. 1995; Pick, Jr. et al. 1999]. The Pick et al. [1999] experiments consisted of a pre-test, recalibration phase, and a post-test. The pre- and post-tests were identical and involved having the participants note the direction they were facing in a room, close their eyes, and rotate in place until they thought that they were facing the same direction again (i.e., a 360 degree turn). The number of degrees the participant turned was recorded by the experimenter. During the recalibration phase, participants turned in place for seven minutes on a turntable mechanism that caused their view of the room to rotate at a rate different than their stepping rate. For example, in one condition participants stepped at a rate of 10 rpm while seeing the environment rotating at 5 rpm and experienced a situation that was visually twice as slow as their biomechanical stepping rate. This caused participants to calibrate their rotational locomotion to a slower rate of rotation than they typically would experience for their stepping rate. As a result, participants rotated farther in the post-test than they did in the pre-test (compared to a condition where the visual and biomechanical rates of rotation were matched). However, because the vestibular cues for rotation matched the visual cues in the Pick et al. [1999] experiments, it is unclear if visual-motor recalibration, vestibular-motor recalibration, or some combination of the two occurred.

Ivanenko et al. [1998] and Viaud-Delmon et al. [1999] have indicated visual-vestibular rotational recalibration might occur when participants viewed a world moving at one rate while they were passively rotated by a mechanical device. During their recalibration phase, subjects viewed a virtual room which rotated faster or slower than physical rotation. In the pre- and post-tests, subjects were passively rotated while blindfolded and then indicated the amount of perceived rotation with an angular pointer. When the visual information rotated slower than the physical rotation during the recalibration phase, subjects indicated that they perceived less rotation in the post-test relative to the pre-test. Unlike Ivanenko et al. [1998] and Viaud-Delmon et al. [1999], subjects actively stepped to turn themselves in the present work. Therefore, both visual-vestibular and visual-motor recalibration could occur in the present work.

This work expands on previous work [Kuhl 2004] to demonstrate that rotational recalibration can occur in IVEs and examines how people might simultaneously recalibrate left and right rotations differently. The primary motivation of this work is to explore basic perceptual issues involving the perception-action coupling for rotational locomotion in virtual environments. A secondary motivation is to help us understand how rotational recalibration might influence previous work [Razzaque

et al. 2001; Williams et al. 2006a; Williams et al. 2006b] that uses a mismatch between actual locomotion and visually indicated movement to allow VE users to naturally explore a large virtual space in a smaller real space. Although this can increase the amount of naturally explorable space, recalibration has the potential to affect the utility of this approach. For example, if a user experiences a particular rotational visual/locomotive mismatch for an extended period of time, recalibration would influence the ability of a user to subsequently perform an accurate rotation without vision.

2. EXPERIMENT DESIGN

The experiment design for all of the experiments presented in this paper consisted of a pre-experiment procedure, a pre-test, a recalibration phase, and a post-test. Prior to all experiments, participants were assisted in walking while wearing a blindfold for approximately five minutes. This helped participants become comfortable walking around in an environment without visual information and trust that the experimenter would not allow them to walk into obstacles. During this task, participants were told to walk straight ahead. When they approached a wall, the experimenter told the participant to stop, turned them away from the wall, and then told the participant to resume walking forward.

Participants were next told to only rotate in place for the remainder of the experiment. Most participants were able to stay in the center of the room for the experiment. However, some participants occasionally needed to be guided back to the center of the room after they drifted near the edge of the tracked space. If participants did translate in the environment, the virtual environment correctly showed their translation. As a result, if participants drifted away from their starting position, care was taken to ensure that they were assisted back toward the center of both the real space and virtual space with their eyes closed. Participants viewed the virtual environment with a Kaiser Electro-Optics Proview XL50 HMD that provided a 40x30 degree field of view and weighed approximately one kilogram (2.2 pounds). All participants wore headphones that played static to prevent them from using audible landmarks to determine how far they were rotating. Directions given by the experimenter were conveyed to participants through the headphones so that participants could not localize the experimenter acoustically.

In the pre-test, participants were told to look around at the small virtual room (shown in Figure 1) that they were standing in. The participants were all initially facing the same poster (a green ‘C’) in the virtual room. They were told to view this poster until they felt they had a good idea of where the poster was. Next, the participants closed their eyes, the HMD graphics were turned off, and they were told to turn to their left or right (depending on the experiment condition) in a complete circle until they thought they were facing the same poster again (a 360 degree rotation). Participants were told not to determine how far they rotated by counting the number of steps they took. We instructed participants to try to make the full rotation without making minor adjustments after their rotation. We measured the direction the participant was facing before and after their rotation. These measurements were used to calculate the number of degrees the participant turned.

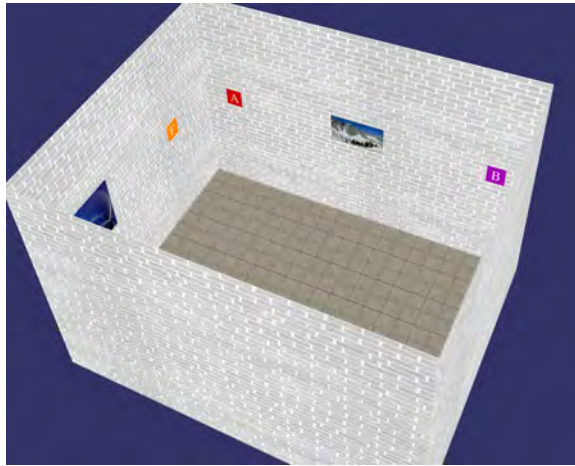


Fig. 1. Aerial view of the virtual room (ceiling removed)

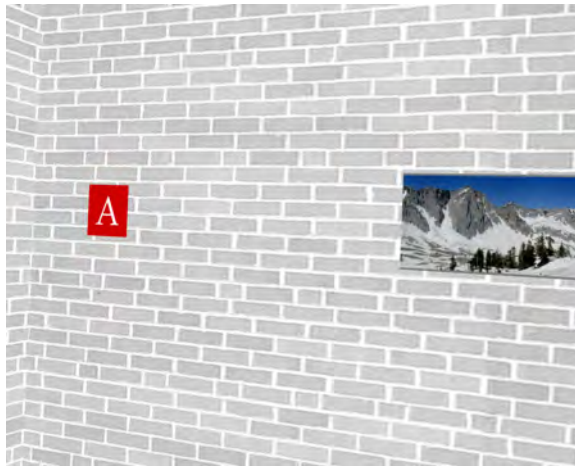


Fig. 2. A participant's view of the virtual room

In the recalibration phase, the rate of physical and visual rotation was either matched (Experiment I) or mismatched (Experiments II and III). The coupling between physical and visual rotation rates was not described to participants prior to or during the experiments. During the recalibration phase, participants followed a series of thirty instructions given verbally by the experimenter. Each instruction told the participants to turn left or right with eyes open until they saw a particular lettered poster in the virtual room. For example, “Turn right until you see the black poster with an E on it.” Participants were allowed to rotate their head as much as they wanted to. However, they were required to turn their whole body (not just their head) until they were facing directly at the virtual poster. The participants were given the next instruction after they had completed the rotation for the previous one. They were allowed to complete the series of instructions

as slowly or as quickly as they desired. It typically took about ten minutes for participants to complete the recalibration phase in all of the experiments.

We repeated the pre-test procedure for the post-test. Participants were told to not look around while initially viewing the poster before closing their eyes and rotating. Any small rotations that participants might have made before closing their eyes in the post-test had the same visual-biomechanical mismatch as that used during the recalibration phase. Participants in Experiment I and II turned in one direction in the pre- and post-tests and participants in Experiment III turned in both directions. We chose not to have participants perform many trials in the pre- and post-tests to prevent the recalibration effect from diminishing. The following equation was used to compute the magnitude and direction of recalibration:

$$\left(\frac{\text{degrees turned in post-test}}{\text{degrees turned in pre-test}} - 1 \right) \cdot 100\%$$

The virtual room was rectangular shaped and 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 participants saw the world (with the HMD’s field of view).

3. EXPERIMENT I: CONTROL

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

3.1 Method

A workstation with an nVIDIA GeForce Ti 4200 graphics card simultaneously rendered the left and right eyes at a resolution of 1024x768 and 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 list of instructions given to the user during the recalibration phase was created by randomly selecting a poster and a direction of rotation thirty times. Next, the list was adjusted such that the participant would turn the same total amount to their left as they did to their right during the recalibration phase. This reduced the possibility of participants becoming tangled in the cables connecting the HMD to the computers. The same list was used for all participants.

Sixteen undergraduate students and staff from Augsburg College participated in this experiment (7 females and 9 males). Half of the participants performed one left turn in both the pre- and post-tests. The remaining participants performed right turns. Participants were able to see the laboratory space prior to practicing blindfolded walking.

3.2 Results

No recalibration occurred when visual and biomechanical rotation rates were matched in the recalibration phase. For left and right turns respectively, participants turned 3% less and 1% further in the post-test than the pre-test. When left and right turn data is combined, participants turned 1% less in the post-test than the pre-test. Paired t-tests between the pre- and post-tests for left and right turns indicated that our HMD-based IVE does not cause rotational recalibration when biomechanical and visual rotation rates match (left turn $t(7) = 1.63, p = 0.15$; right turn $t(7) = -0.13, p = 0.90$).

These results differ from those found in the visual/biomechanically matched condition conducted by Pick et al. [1999] using a turntable in the real world. In their experiments, participants rotated in place at a mechanically set rate in one direction during the recalibration phase. This may have triggered a sensory adaptation-like mechanism that caused participants to turn shorter or farther in the post-test than the pre-test depending on if the pre- and post-tests were in the same or opposite direction of rotation used in the recalibration phase. Our results show that this effect does not occur when the participants are able to turn in both directions naturally during the recalibration phase.

4. EXPERIMENT II: RECALIBRATION OF YAW

Experiment II was designed to determine how people recalibrate to environments in which the rate of yaw rotation is visually twice as fast or twice as slow. The recalibration phase for half the participants (3 females and 5 males) was visually twice as fast as their biomechanical rotation rate. For the other half (4 females and 4 males), it was visually twice as slow. Half of each of these two groups turned to the right in the pre- and post-test and the other half turned to the left.

4.1 Method

Experiment II used the same HMD, tracker, computer system, and recalibration phase instructions used in Experiment I. Each of the sixteen participants that participated in Experiment I returned on a later date to participate in this experiment.

4.2 Results

The results from the visually faster condition are indicated by the left two bars in Figure 3. When the results of left and right turns are combined, participants turned 13 percent less in the post-test relative to the pre-test. In absolute terms, participants turned approximately 45 degrees less in the post-test than the pre-test. The visually slower condition results are indicated by the right two bars in Figure 3. When left and right turns are combined, participants turned 13 percent more in the post-test relative to the pre-test. A 2 (conditions) x 2 (directions of rotation) ANOVA was performed on the data. The visual condition had a significant influence on the amount of recalibration ($F(1, 12) = 26.54, p < 0.01$). However, the amount of recalibration was not significantly influenced by the direction of rotation ($F(1, 12) = 2.37, p < 0.15$) or the interaction of direction and condition ($F(1, 12) = 0.15, p < 0.70$).

It is difficult to quantitatively compare our results with those of Pick et al. [1999]

for two reasons. First, Pick et al. [1999] found that a sensory adaptation-like recalibration occurred in their experiments. However, Experiment I demonstrated that the same effect did not occur in our experiments. Second, the vestibular rate of rotation matched the physical rate of rotation in our experiments but matched the visual rate of rotation in the Pick et al. [1999] turntable experiments. Despite these differences, the present experiment and Pick et al. [1999] demonstrate that rotational recalibration occurs and that the magnitude of recalibration was significant but did not approach a complete recalibration of turning half or twice as far in the post-test relative to the pre-test.

There are at least two methods that may have been used by participants to determine how far they have rotated in the post-test. First, participants may have ignored biomechanical information from stepping and instead used vestibular information to estimate the amount that they have rotated. If visual-vestibular recalibration occurred during the recalibration phase, this method could have caused the results seen in this experiment. Previous work suggests that this type of recalibration may occur [Ivanenko et al. 1998; Viaud-Delmon et al. 1999]. Alternatively, participants may have ignored vestibular information and simply stepped until biomechanical information indicated that they had stepped in a complete circle. If visual-motor recalibration occurred during the recalibration phase, this method could have also caused the results seen in this experiment. Finally, it is also possible that participants used a combination of both of these approaches to determine how far to rotate.

5. EXPERIMENT III: DIRECTIONALLY DEPENDENT RECALIBRATION OF YAW

Experiment III was designed to determine how people recalibrate to a virtual environment that rotates at a different rate as a function of direction of turning (to the left or right). Specifically, we examined a situation where the virtual world

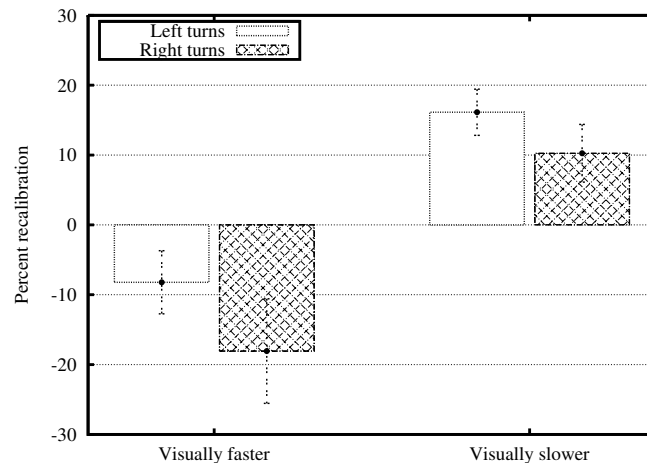


Fig. 3. Experiment II: Recalibration occurred when the visual rotation rate was twice or half the biomechanical rotation rate. Error bars indicate \pm one standard error of the mean.

rotates visually two times faster in one direction of rotation and visually half as fast in the other direction. If people recalibrate left and right rotation completely independently, we would expect that they would turn approximately thirteen percent less in the post-test than the pre-test if they were turning in a direction that was visually twice as fast. Likewise, when participants turned in a direction that was visually half as fast in the recalibration phase, we would expect that they would turn approximately thirteen percent more in the post-test than the pre-test. Alternatively, if people do not recalibrate left and right rotations independently, it is possible that a visually faster rotation in one direction and a visually slower rotation in the other direction might cancel each other out.

Previous work suggests that the visual-vestibular recalibration of left and right rotations do not occur independently [Viaud-Delmon et al. 1999]. However, it is currently unknown what the relationship is between left and right rotational recalibration. Knowledge about this relationship may be useful for IVEs that use different mismatches for left and right rotation to increase explorable space. The first condition investigates how people recalibrate to visually faster left turns and visually slower right turns, replicating the results of Kuhl [2004]. To help further determine the relationship between the recalibration of left and right turns, the second condition investigates recalibration to visually slower left turns and visually faster right turns.

5.1 Method

Unlike the previous experiments, the graphics were driven by two clustered PCs with nVidia GeForce 6800 Ultra video cards. The graphics were rendered at a rate ≥ 60 frames per second during the experiments. An InterSense IS-900 motion tracker was used to determine the position and orientation of the HMD within a 7x10 meter tracked space.

Experiment III had a similar design as the previous experiment with several significant differences. Instead of performing one rotation in the pre- and post-tests, participants performed two pre-tests (one left turn and one right turn) and two post-tests (one left turn and one right turn) in this experiment. Half of the participants turned left first in the pre- and post-tests and the other half turned right first. The procedure for the pre- and post-tests was similar to the previous experiments: Participants viewed a virtual poster, closed their eyes, and turned to their left or right with their eyes closed until they thought that they were facing the poster again. When the participant stopped turning, we recorded the amount they turned with the tracking system. Next, we asked participants to reverse the turn that they just performed to help limit cables getting tangled around them. After they finished reversing their rotation, participants opened their eyes. They were asked to face directly at the nearest virtual poster that they could see. Finally, the participant performed the second rotation with eyes closed in the opposite direction of their first rotation.

In the recalibration phase for the previous experiments, participants turned the same amount to their left as they did to their right (both visually and physically). The instructions were changed for this experiment so participants would *physically* turn approximately the same amount to their left and right. Kuhl [2004] had participants rotate the same amount *visually* left and right over the recalibration phase.

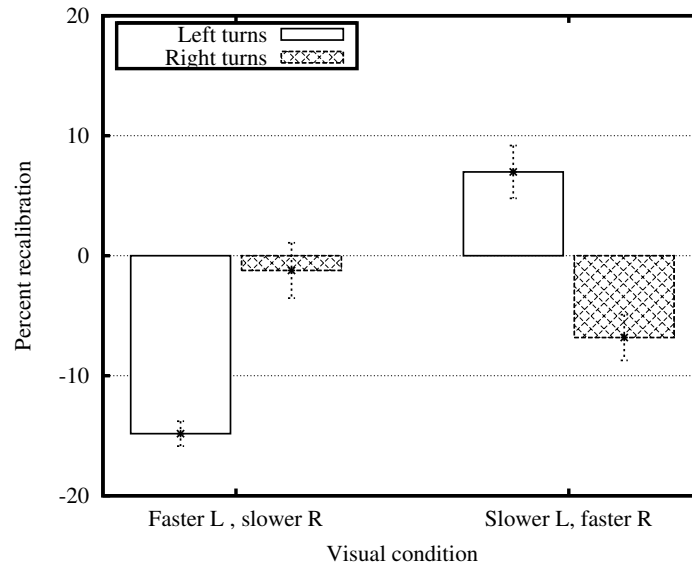


Fig. 4. Experiment III: Left and right rotations were recalibrated differently but were not recalibrated independently of each other. Error bars indicate \pm one standard error of the mean.

This caused people to physically rotate more in the visually slower condition and required the experimenter to loop cables over the participant’s head periodically to prevent them from getting tangled. The instructions used in the present experiment greatly reduced the problem.

Sixteen University of Utah undergraduate psychology students participated as participants in this experiment. Eight of these participants (3 females and 5 males) experienced visually faster left turns and visually slower right turns. The remaining participants (4 females and 4 males) experienced visually slower left turns and visually faster right turns. Unlike previous experiments, participants were blindfolded prior to entering the laboratory space so as to reduce possible interference between memory of the physical space and perception of the virtual space.

5.2 Results

The first two bars in Figure 4 show the results for the 2x visually faster left rotations and 2x visually slower right rotations. These results are qualitatively similar to those of Kuhl [2004] despite the significant differences in the experiment design and are further evidence to suggest that left and right rotations are not independently recalibrated. The results of the opposite condition (visually slower left turns and visually faster right turns) are shown in the last two bars in Figure 4.

Unlike Experiment II, where both the direction of rotation and condition were between-participant variables, this experiment measured both directions of rotation for each participant. Therefore, we used a repeated measures 2 (conditions) \times 2 (directions of rotation) ANOVA with the condition as a between-participant variable and the direction of rotation as a within-participants variable. A significant interaction between the visual condition and direction of rotation ($F(1, 14) = 74.33$,

$p < 0.01$) indicates that there was some symmetry in the results of the two conditions. This can be seen visually as the symmetric difference between left and right recalibration for both of the Experiment III conditions in Figure 4. In both conditions, the average unsigned difference between left and right recalibration was 14%. There was also a significant difference in the amount of recalibration found in the two conditions ($F(1, 14) = 13.45$, $p < 0.01$). This difference can be seen in Figure 4 as the vertical shift of both the faster and slower bars from the first condition to the second. The direction of rotation did not significantly influence the amount of recalibration ($F(1, 14) = 0.004$, $p < 0.95$).

These results are consistent with the idea that there may be multiple couplings being recalibrated. For instance, it has been shown that the visual-vestibular system can be recalibrated to mismatched rates of visual and vestibular rotation [Ivanenko et al. 1998; Viaud-Delmon et al. 1999]. Because the perceived rate of rotation from the vestibular system matches the physical rate of rotation from stepping in the present work, it is possible that both visual-vestibular recalibration and visual-motor recalibration is occurring simultaneously. Viaud-Delmon et al. [1999] indicates that the visual-vestibular system might not be able to recalibrate left and right rotations independently. However, visual-motor recalibration might allow for independent recalibration of left and right rotations. Therefore, this work suggests that left and right rotations can be separately recalibrated although they are not fully independent and that multiple perceptual systems might be recalibrated differently.

6. ADDITIONAL RESULTS

When the pre-test data for Experiments I–III are combined, we find that participants rotated an average of 95.1 percent of a full circle. A t-test indicates that this value was significantly less than a full rotation ($t(31) = -4.45$, $p < .01$). This indicates that participants overestimated their perceived amount of rotation in the pre-test. It is important to note that this particular result has no direct impact on the experiments because the amount of recalibration was computed as a ratio of the amount turned in the post-test to the amount turned in the pre-test.

The participants' overestimation of the amount that they had actually turned is consistent with previous work. A control condition by Bles et al. [1984] found a similar overestimation of 360 degree turns in the real world. The overestimation of rotations is not unique to rotating in place by stepping. Previous work [Israël et al. 1995] found that overestimation of perceived rotation also occurred when participants controlled a mechanical device that rotated participants in place. Lastly, Jaekl et al. [2003] also suggested that people overestimate rotations by showing that participants perceived virtual environments that rotated 20% faster than physical rotations as the most perceptually stable.

In the present work, participants were asked if they felt physical sensations such as dizziness or nausea during the experiment. Forty percent reported that they experienced slight dizziness or eye strain. This result was expected due to both the large number of repeated rotations participants performed and the mismatched physical and visual rotation rates. No participants reported that they experienced large amounts of dizziness, nausea, or eye strain.

After Experiments II and III, participants were asked if they noticed anything strange about how they were rotating in the virtual room or if there was anything that could be improved in the virtual environment to make it more realistic. The majority of people answered that they thought they were rotating in the virtual room just like they would have in a real room. Although previous work [Ivanenko et al. 1998; Viaud-Delmon et al. 1999] has shown that visual-vestibular mismatches are often unnoticed by participants, this work indicates that visual-motor mismatches are also often unnoticed. Approximately 20 percent explained that they thought that the posters might have been moving around the room. This suggests that these participants perceived the virtual world moving with respect to a real world reference frame. Another 15 percent of the participants 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 participants were able to recognize that the gain between visual and physical rotation changed depending on the direction they rotated in the recalibration phase. Some of these participants reported that one direction of rotation felt normal and the other direction felt slow or fast even though one direction was visually faster and the other was visually slower. There was not enough data to determine how these participants might have determined which direction felt normal.

Even if the participants had said that they saw nothing strange during the recalibration phase, many participants immediately realized that they did notice the virtual world moving strangely after the visual/biomechanical mismatch effect was explained to them after the experiment was complete. This suggests that participants 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.

Virtual environments can potentially be improved by using the fact that it is difficult for the human perceptual system to notice mismatches between visual and physical rotation rates. For example, others [Razzaque et al. 2001; Williams et al. 2006a; Williams et al. 2006b] have shown that mismatched physical and visual movements can allow HMD users to naturally explore a virtual space larger than the physical space they are walking in. The present work indicates that rotational recalibration should be considered during the design of a system that uses mismatched physical and visual rotation rates for extended periods of time.

7. SUMMARY

These experiments show that people recalibrate in IVEs in a way that is qualitatively similar to how people recalibrate in the real world. By using the IVE, we were able to recalibrate the perception-action coupling while removing the sensory adaptation-like mechanism of recalibration that occurs when participants rotate on a turntable at a mechanically set rate. Experiment III indicates that more research is needed to fully understand how people simultaneously recalibrate left and right rotations when there are different visual/biomechanical discrepancies for the two directions. The results suggest that visual-vestibular and visual-motor recalibration might be occurring simultaneously. We have also shown that the majority of partici-

pants do not notice discrepancies in visual and physical rotations. Finally, this work provides a basic background on the implications of using a visual/biomechanical discrepancy for rotations to allow people to explore a virtual space larger than the physical tracked space.

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