

The Recalibration of Rotational Locomotion

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Rotational locomotion (i.e., turning in place) can be recalibrated by arranging a situation in which one steps around at 1 speed but turns through the world at a different speed. After exposure to such a situation, people will show predictable changes if asked to look at a target, close their eyes, and turn to face it. In 5 experiments, this recalibration was shown to be attributable to 2 different mechanisms, one a sensory adaptation-like component from simply turning in place for several minutes and the other a perceptual-learning-like component related to the discrepancy created by the rearrangement of optical flow and action.

For the most part, people's interactions with the physical world are relatively safe and graceful and merit comment only when something goes wrong and they have an accident. Thus, people hardly note when they arrive safely across the street or pour a glass of beer for a guest. These are in fact remarkable achievements, as many would-be robot constructors know. "Why is this surprising?" is a common reaction to such achievements. "You can see what you are doing." An intriguing aspect of such actions is that people can often accomplish them successfully even when they cannot "see" what they are doing. People can even perform them without specific concurrent perceptual input of any kind, such as when they stagger with their eyes closed in the middle of the night to the refrigerator for a snack or when they reach to the shelf behind them for a stapler without looking. In these cases people seem to be adjusting their actions to the direction, distance, size, weight, and so on of the objects and places in the world on the basis of their previous knowledge (or short-term memory) about them, as opposed to their immediate perception. Attneave and Farrar (1977) remarked on this and demonstrated it experimentally. Participants were asked to indicate, by moving a switch, the left-right direction and orientation of previously viewed objects arrayed behind them. Attneave and Farrar found that participants could do this almost as rapidly as they were able to do it while they were still facing the objects (albeit occluded by a curtain). One implication of these results is that participants' left-right judgments were adjusted to account for their movement from facing these objects to turning around and facing in the other direction.

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The present article is concerned with the processes involved in such updating of people's own movements when interacting with the environment. In particular, consider what is required to perform spatially appropriate actions with respect to unseen locations after a person has moved. Besides knowing the layout of these locations, one must also know how one has moved within the environment. Rieser, Pick, Ashmead, and Garing (1995) investigated how the perceptual consequences of a walking activity might serve to calibrate people's translatory locomotion. The prototype paradigm involved observers stepping at one (e.g., rapid) biomechanical rate but experiencing themselves actually moving through the world at a different (e.g., slower) rate. After exposure to several minutes of such a discrepancy, their calibration between perceived distance and walked distance was changed. This calibration was manifest when they looked at a target, closed their eyes, and attempted to walk to it. They reliably overshot the goal and walked too far.

Is this a general phenomenon of perception and action, or does it apply only to translatory locomotion? To explore the generality, similar effects were sought by Rieser et al. (1995) for throwing action and for rotational locomotion. In the latter case, observers standing at the center of a turntable stepped around in place at a rapid stepping rate but actually turned through the world at a slower rate because of counterrotation of the turntable. After several minutes of such experience, the turntable was stopped and observers were asked to look at targets, close their eyes, and turn one complete revolution until they were facing the target again. As with the translatory locomotion, observers reliably overshot the goal and turned too far. It was as if the experience of stepping rapidly and turning slowly had taught the observers that in order to turn a given angle to face some object, they needed to step much more than they previously had done. In that sense their rotational locomotion was recalibrated.

The purpose of the present research was to examine more thoroughly the processes involved in this rotational recalibration. Five experiments are described. The first experiment

essentially replicated and extended the initial rotational recalibration experiment of Rieser et al. (1995). In the subsequent experiments we attempted to identify two possible recalibration mechanisms.

Experiment 1

The purpose of Experiment 1 was to confirm that rotational recalibration would occur under a condition in which participants were stepping to turn in place at a faster rate than they were actually rotating in the environment. As in Rieser et al. (1995), this was achieved by having participants stand in the center of a turntable grasping, and keeping up, with a bar rotating at one rate while the turntable was counterrotating. Thus, as they stepped to keep up with the bar, their forward progress in the environment was diminished by the counterrotation of the turntable. To assess recalibration, we measured participants' accuracy in turning to face targets before and after they experienced the discrepancy between stepping rate and turning rate. We predicted that a participant would tend to overshoot after experiencing such a discrepancy compared with his or her performance beforehand. This experiment extended that reported by Rieser et al. by testing for recalibration while participants stepped in the direction opposite to that during the discrepancy experience as well as in the same direction.

Method

Apparatus. The apparatus consisted of a turntable having a 122-cm diameter disk, mounted on a 35-cm-high metal housing for two motors. A T-bar was mounted on a post extending vertically through the center of the turntable (see Figure 1). The post of variable length was adjusted to be waist high for each participant. One motor was linked by a chain drive to the T-bar post that could be driven at variable speeds in either a clockwise or counterclockwise direction. The second motor was linked by a friction drive to the turntable, which could also be driven at variable speeds in either direction.

To generate the discrepancy between stepping and turning, the T-bar was driven at one rate (in this experiment, 5 rpm) and the turntable counterrotated (in this experiment, 5 rpm). Thus, a participant would experience stepping at 10 rpm to keep up with the T-bar but would be turning through the environment at 5 rpm. For assessing the accuracy of the direction of the participant was facing, the T-bar post could be disengaged from the motor drive and the T-bar would turn freely as the participant stepped around the stationary turntable to face targets.

Participants. Participants were 8 undergraduate students who were paid a nominal amount for their time. None had previously participated in this kind of experiment.

Design and procedure. The basic design consisted of three phases: a pretest in which facing accuracy was measured, a discrepancy or rearrangement phase, and a posttest in which facing accuracy was remeasured. On entering the experimental room, participants were shown the turntable and T-bar and were told that this was an experiment to study the calibration of locomotion. They were also told that they would be asked to step on the turntable, grasp the T-bar, and hold it against their waist. Sometimes during the procedure the T-bar itself would be rotating, in which case participants' were to keep stepping and hold it against their waist, and sometimes it would turn freely and they would be asked to look



Figure 1. Turntable apparatus (optokinetic curtain was not used in the experiments).

at targets and step around with their eyes closed until they were again facing the same target. The experimenter demonstrated these procedures and then encouraged the participants to try it themselves. They were also told that the turntable would sometimes be rotating at the same time as the T-bar and that they should step as necessary to keep up with the T-bar while holding it against their waist.

The procedure during the pretest and posttest was exactly the same. Participants were asked to step up on the turntable, to grasp the freely turning T-bar, to step around for a few seconds with their eyes closed, and then to stop. They then opened their eyes and were asked to note what they were facing in the room. They were then asked to close their eyes and step around one complete revolution until they were facing the same thing again, keeping their eyes

closed the entire time. They were instructed not to use any kind of step-counting strategy in their turning. After their facing direction was recorded, they were instructed to continue stepping with their eyes closed first in one direction and then in the other for a few seconds to disorient them enough to prevent them from getting a good sense of how accurate their judgment had been. After this, they stopped and opened their eyes and the process was repeated. In this manner four clockwise trials were interlaced alternately with four counterclockwise trials, with the experimenter instructing participants which way to turn on each trial.

At the end of the pretest, participants were told that the next phase would be one in which the T-bar and the turntable would both be turning under their own power. They were to continue grasping the T-bar and to step so that they could hold it continuously against their waist. They were then asked to close their eyes again and the T-bar was started. After a few seconds passed and they were comfortably stepping, they were told that the turntable would be started. The counterrotation of the turntable was started and in a few seconds after they were comfortable with this motion, they were told to open their eyes. They stepped with eyes open in this rearrangement phase continuously for 7 min. The visual environment for this, as well as the other experiments reported in this study, was a large, cluttered laboratory room. From time to time during this phase, they were asked to pay attention to where in the room they were facing and how they were turning with respect to the room. After the 7 min had passed they were told to close their eyes and the turntable and T-bar were stopped, and the posttest procedure was begun and carried out exactly as in the pretest. Participants were videotaped from above for each pretest and posttest trial, and facing direction was determined by measuring the orientation of the T-bar from the monitor with a protractor. The angle could be read to the nearest 2°. (This measurement procedure was followed for Experiments 1, 2, and 3.) To eliminate audition as a source of directional information throughout the entire experiment, we had participants wear padded earphones, through which both ambient noise from the environment and instructions were heard via a microphone. In preliminary tests participants were unable to localize the source of sounds in the room. (This procedure was followed in all the experiments in this research.)

At the end of the posttest the participants opened their eyes, stepped off the turntable, and were debriefed first with questions about strategies they used to decide how far to turn, then about what they experienced during the rearrangement phase, and about any general observations they had. Finally, the general nature of the experiment was explained and they were thanked for their participation.

Four participants stepped in a clockwise direction during the rearrangement phase and 4 stepped in a counterclockwise direction, and all stepped at a rate of 10 rpm while turning through the environment at 5 rpm in the same direction. This condition is referred to as biomechanical-rate-faster-than-turning-rate, or the "biomechanically faster condition."

Results

The quantitative results were based on the pretest and posttest measures of facing direction. To determine whether the rearrangement phase induced any overall change in the amount of stepping to turn one complete revolution, we subtracted the average amount of turn for the pretest trials from the average for the posttest trials. For each participant, this change score was calculated separately for turns in the same direction as the stepping in the rearrangement phase and for turns in the opposite direction as the rearrangement phase stepping. Thus, there were two average change scores for each of the 8 participants. The average change score for the same direction stepping was +92.1° (±35.2°) and for the opposite direction stepping, -12° (±32.9°). Positive values indicate walking farther after the rearrangement phase than before (i.e., a greater tendency to overshoot). All 8 participants showed this tendency in the same-direction tests, whereas only 3 participants did in the opposite-direction tests (see Table 1). Statistical analysis supported these apparent results. The confidence bounds indicated that the same-direction change was clearly greater than zero and that the opposite-direction change was not. A *t* test between

Table 1
Degrees of Error When Attempting to Step One Full Turn (95% Confidence Intervals Appear in Parentheses)

Experiment	Same direction tests ^a			Opposite direction tests		
1. Recalibration is directionally selective	92 (±35)			-12 (±33)		
2. Smaller recalibration for the matched speed ^b than legs faster condition	Matched speed 34 (±23)	Legs faster 44 (±20)		Matched speed -30 (±20)	Legs faster -25 (±20)	
3. Bidirectional ^c change in calibration	One directional 61 (±31)	Bidirectional 25 (±14)		One directional 7 (±13)	Bidirectional 45 (±27)	
4. Attention to the environment affects the legs faster condition, not the matched speed condition	Matched speed 23 (±28)	Legs faster 98 (±20)		Matched speed -22 (±26)	Legs faster 1 (±25)	
5. Attending to environmental flow affects the legs faster and legs slower condition, not the matched speed condition	Matched speed 8 (±14)	Legs faster 79 (±36)	Legs slower -32 (±54)	Matched speed -1 (±17)	Legs faster 0 (±19)	Legs slower -31 (±25)

^aDuring the same direction tests, participants stepped in the same direction as during the recalibration phase, and the opposite was the case in the opposite direction tests. ^bFor the recalibration phases, the following applied: during the matched speed condition, participants stepped so that their rates of biomechanical activity were the same as their rates of environmental flow; during the legs faster condition, biomechanical rates were faster than environmental flow; in the legs slower condition, biomechanical rates were slower than environmental flow. ^cDuring the bidirectional condition of the recalibration phase, participants walked in one direction, then the other, and so forth, alternating between the clockwise and counterclockwise directions. See text for meaning of same and opposite direction in this condition.

the changes in the two directions indicated that the same-direction change was reliably greater than the opposite-direction change, $t(7) = 4.7, p < .01$.

Discussion

The results clearly confirm those of the original rotational calibration experiment of Rieser et al. (1995). Substantial overshooting occurs when rotational locomotion is tested in the same direction as the rearrangement stepping. The present experiment provides one additional and intriguing fact beyond that original experiment: the sharp contrast between the results for the two directions of stepping. The overshooting appeared to occur only when the locomotion was tested in the same direction as the stepping during the rearrangement. The present results appear to indicate no change when locomotion was tested in the opposite direction. Why did this directional specificity occur?

We now consider what sort of mechanisms might underlie recalibration. One mechanism might be a kind of sensory adaptation, resulting in a sensory aftereffect that could manifest itself in the sort of recalibration measured here. How might such a mechanism work? Suppose that there were a bank of feature-like detectors, perhaps biomechanical feature detectors, that were sensitive to different rates of stepping, ranging from rapid clockwise stepping to slow clockwise stepping, to slow counterclockwise stepping, to rapid counterclockwise stepping. Prolonged exposure to one value of stimulation would greatly fatigue the detectors most sensitive to that value and to a lesser extent detectors most sensitive to nearby values, and so on, with a sort of generalization gradient of fatigue. As has been suggested for such sensory detectors, prolonged stimulation of a specific detector could be manifest in both a decreased sensitivity to the particular stimulation value and a shift in the neutral point along this dimension (von Bekesy, 1960). Such phenomena have been demonstrated in the case of tilt adaptation (Gibson & Radner, 1937; Mitchell & Blakemore, 1972) and curvature adaptation (Gibson, 1933). In the case of curvature adaptation, for example, prolonged stimulation with a particular value of curvature results in that stimulus appearing less curved, a straight line appearing curved in the opposite direction, and a real curve in the opposite direction appearing more curved than it had before the prolonged stimulation.

Applying this as a model for locomotion rate, prolonged stimulation at one stepping rate would cause that rate to appear less and rates in the opposite direction to appear greater. Suppose prolonged stepping at a particular rate leads to that rate appearing to be less to the stepper than it did initially. If the stepper were asked to turn a given amount, he or she would tend to overshoot. Another implication of such a mechanism is that, if asked to turn a given amount in the opposite direction, a person showing such overshoot in the stepping direction should show an undershoot in the opposite direction. In the case of Experiment 1, there was not an undershoot in the opposite direction; there was just no change. Therefore, this kind of adaptation-like mechanism does not appear to account for the results, at least by itself.

An alternative account for recalibration results might be based on a perceptual-motor learning-like mechanism (Hay & Pick, 1966; Redding, Clark, & Wallace, 1985). Such a mechanism would be more cognitive in nature. The idea is that some part of the system guiding the individual's locomotion and navigation registers (e.g., on the basis of visual feedback) how far he or she moves with a certain amount of activity, that is, a system sensitive to perceptual-motor correlation. Clearly, such a system can work at a conscious level. A person usually knows that he or she is exerting more force to bicycle up a hill than when he or she is on a level surface. However, it may also operate unconsciously. One may simply register how far he or she has moved with a certain amount of activity without really thinking about it. In Experiment 1 participants may simply have registered that it took more time to turn the same distance visually than it had normally done or that it took more steps to turn a given amount, even without specifically counting. Then when they tried to turn one revolution in the posttest, they turned for a longer time or for more steps. This would predict the results obtained in the same-direction test, but what about the opposite direction? A cognitive perceptual-motor learning mechanism would most probably predict overshooting in the opposite direction as well. Intuitively, it seems reasonable that if one learns that stepping at a particular rate to the right produces a certain amount of movement to the right, one would assume that the same thing happens if one turns in the opposite direction. That is, the world tends to be physically isometric on a horizontal plane. Even at an unconscious level, a reasonable hypothesis would be that there ought to be some positive transfer to the opposite direction (i.e., an overshoot in the opposite direction). As noted, that did not occur in Experiment 1. There was no significant effect in the opposite direction.

Now suppose, however, that both hypothetical mechanisms were operating, a sensory adaptation-like mechanism and a perceptual-motor learning-like mechanism (e.g., Harris, 1980).¹ This might be the case in the original rotational experiment of Rieser et al. (1995) and Experiment 1 here, in which the sensory adaptation effect would arise directly through the activity of stepping and the perceptual-learning effect would occur depending on how naturally observant the participants were. The two effects would work together to produce robust changes in the same direction, but in the opposite direction they would work against each other and perhaps neutralize each other. What kind of evidence would support the possible existence of such hypothetical mecha-

¹ An earlier hypothesis of two mechanisms of adjustment to perceptual rearrangement similar to the one being suggested here was proposed for the case of adaptation to the curvature produced by wedge prisms. One component analogous to the sensory adaptation mechanism was considered to arise simply from exposure to curved lines (even if there was no actual perceptual-motor rearrangement). The other component was considered to arise from rearrangement when a new motor response comes to be appropriate to a particular stimulus (e.g., moving in a straight line to follow a curved line or path). (See Burnham, 1968; Festinger, Burnham, Ono, & Bamber, 1967; Held & Rekosh, 1963; and Welch, 1978 for evidence and discussion.)

nisms? A perceptual-motor learning mechanism would likely be enhanced by an attention manipulation in which the new correlation between stepping and movement through the environment is made more salient. We attempted this in Experiments 4 and 5. A sensory adaptation-like effect should be reduced or eliminated if participants could recalibrate simultaneously in both directions. Such a possibility was investigated in Experiment 3. A sensory adaptation-like mechanism should be operative even when there is no discrepancy between stepping rate and turning in the environment. Prolonged stepping by itself should result in measured recalibration. This possibility was examined in Experiment 2.

Experiment 2

In Experiment 2 the effect of stepping without any discrepancy between stepping rate and turning rate was compared with the biomechanically faster stepping condition of Experiment 1.

Method

Participants. Sixteen undergraduates were paid a nominal sum for their participation in this experiment.

Apparatus, procedure, and design. The apparatus and procedure were the same as in Experiment 1. All participants went through a pretest, rearrangement, and posttest phase. However, for 8 participants the rearrangement phase was a null rearrangement (i.e., a matched speed condition, in which the stepping rate was the same as the turning rate). This was accomplished by simply locking the turntable in place. The T-bar was turned at 10 rpm, requiring the participants to step at that rate on the stationary turntable. Recalibration under this condition could be attributed to a sensory adaptation mechanism because there was no discrepancy between stepping rate and movement. The other 8 participants in the biomechanically faster condition, as in Experiment 1, stepped at 10 rpm, but this was accomplished by having the T-bar turn at 5 rpm and the turntable counterrotate at 5 rpm. Half the participants in each condition experienced the rearrangement phase stepping in the clockwise direction and half in the counterclockwise direction. They were all tested for turning to face targets in both the same direction and in the opposite direction as they stepped in the rearrangement phase.

The biomechanically faster condition was expected to replicate previous results and to produce substantial recalibration in the form of overshooting when tested in the same direction as stepping on the turntable when the two mechanisms should be working together. Reduced effects or even undershooting would be predicted when tested in the direction opposite to the stepping during rearrangement, where the two mechanisms are hypothesized to be working against one another. The matched speed condition was expected to produce a sensory adaptation-like phenomenon that would be manifest in overshooting in the same direction test and undershooting in the opposite direction test.

Results

The average overshoot in degrees in attempting to turn 360° (one full turn) is presented in Table 1 (Experiment 2). It is evident from the table that the matched speed condition resulted in a substantial overshoot when tested in the same

direction and a substantial undershoot when tested in the opposite direction.² The overshoot in the biomechanically faster condition was also substantial and somewhat larger than in the matched speed condition, and the undershoot was also substantial but slightly less than in the matched speed condition. The overshoots and undershoots in both conditions were significantly greater than zero, as indicated by the confidence bounds. A two-way analysis of variance (ANOVA) indicated that the overshoots were significantly larger than the undershoots, $F(1, 14) = 5.10, p < .05$, but there was not a significant interaction between the conditions and the test direction.

Discussion

The finding of substantial overshoot in the same-direction measure of the matched speed condition is strong evidence for a sensory adaptation-like mechanism of recalibration. The finding of a substantial undershoot in the opposite direction supports the possibility that adaptation has a dimensional quality like that of curvature or tilt. The pattern (or direction) of results for the biomechanically faster condition is correct in terms of the hypothesis of two mechanisms at work, but the magnitudes were not great enough to provide statistical support. The measure of overshoot in the same direction, 43.9°, was higher than that for the matched speed condition, as would be predicted if a perceptual-motor learning mechanism were summing with the sensory adaptation mechanism, but it was not significantly higher. It was also the case that the undershoot was lower in the opposite direction, as would be predicted if the two mechanisms were working against each other in this condition, but, again, it was not significantly lower.

Experiment 2 provided considerable support for the existence of a sensory adaptation-like mechanism in recalibration. It did not provide strong support for the existence of the other perceptual-motor learning-like mechanism because the pattern for the biomechanically faster condition was so similar to that of the matched speed condition. Would there be another way to demonstrate recalibration that could not be attributed to a sensory adaptation mechanism? In Experiment 3 we attempted to do this.

Experiment 3

Suppose that rotational locomotion of the kind we are dealing with here could be calibrated simultaneously in the clockwise and counterclockwise directions. It would be difficult for the type of sensory adaptation explanation being proposed to account for any recalibration obtained, thus implicating a second mechanism. This was the goal of

² It is possible that overshoot changes such as those reported here are the result of undershoots on the pretest, with performance becoming more accurate on the posttest after stepping on the turntable. This was not the case. For example, in Experiment 1, the pretest measures averaged $-2.9^\circ (\pm 22.5^\circ)$ and, in another similar study not reported here, $4.5^\circ (\pm 15.3^\circ)$. These results are typical; pretest performance is highly accurate and posttest performance shows the effects of the experimental manipulations.

Experiment 3. The rearrangement phase consisted of alternate periods of a biomechanically faster condition, first in a clockwise direction and then in a counterclockwise direction. We hypothesized that alternately stepping in one direction and then the other would cause any sensory-based overshoot from stepping in one direction to be neutralized by the undershoot from stepping in the other and vice versa. If there were an overall remaining recalibration, it would have to be from a second mechanism.

Method

Participants. Fifteen undergraduates participated in this experiment and were paid a nominal amount.

Apparatus, procedure, and design. The same apparatus was used as in the previous experiments. The pretest and posttest procedures were also the same. Two different rearrangement conditions were compared. One was the same as the biomechanically faster conditions of Experiment 1 and 2, in which participants stepped at 10 rpm to turn through the environment at 5 rpm. Seven participants went through this condition, 4 in a clockwise direction and 3 in a counterclockwise direction. In the second rearrangement condition, 8 participants stepped in clockwise and counterclockwise directions in alternate 60-s intervals. In both conditions the rearrangement phase lasted 8 min.

Results

The average overshoot measures are presented in Table 1 (Experiment 3). It is apparent from the data that the results of the unidirectional rearrangement condition did indeed replicate the biomechanically faster conditions of Experiment 1 and 2, in which measures in the same direction as the stepping in the rearrangement phase showed a substantial recalibration and measures in the opposite direction showed less or no change. As suggested before, this could be explained in terms of two mechanisms that summate in the same direction and neutralize each other in the opposite direction.

In the bidirectional rearrangement condition, there was substantial overall recalibration (averaging 35.2°), which, it is argued, could not be based on a sensory adaptation mechanism and could be attributed to a perceptual-motor learning mechanism. Of course, it made no sense in this bidirectional condition to think about tests in the same direction and opposite direction as the rearrangement stepping. However, the overall average overshoot of this condition could be broken down into overshoot in tests in the direction of the most recent (i.e., the last) stepping of the rearrangement phase and tests in the direction of the first stepping in the rearrangement phase. When this was done, the recalibration in the direction of the first stepping direction measured 25° and in the direction of the most recent stepping 46° , as indicated in Table 1. Although this difference was large, it was not statistically significant, $t(7) = 1.92$, $p > .05$. The recalibration in the unidirectional condition was significantly greater than that in the first stepping direction of the bidirectional condition, $t(13) = 12.8$, $p < .05$, but not greater than that in the most recent stepping direction, $t(13) = 0.91$, $p > .05$. A possible explanation for

this difference is that the recalibration decayed rapidly (in the first stepping direction) but then was reinstated quickly (in the most recent stepping direction). However, although the time course of decay was not systematically studied, no rapid decay was observed over the several posttest trials, thus weakening this explanation.

In the matched speed condition of Experiment 2 we attempted to demonstrate a sensory adaptation component to the recalibration when the discrepancy between stepping rate and turning rate was absent. The bidirectional biomechanically faster condition of Experiment 3 was designed to show that there might be a second mechanism for recalibration when the possibility of a sensory adaptation effect was removed. Another way to confirm the presence of this second mechanism would be to enhance it. The hypothesis that it is a perceptual-motor learning mechanism would suggest that, like many perceptual-motor skills, it could be enhanced by calling attention to the information underlying the learning. Experiments 4 and 5 were designed to test this.

Experiment 4

The idea in Experiments 4 and 5 was to make the change in relation between stepping rate and turning rate salient and to even provide practice for the participants in keeping track of where they were as they moved around in the rearrangement phase.

Method

Participants. Sixteen undergraduates participated for nominal compensation.

Apparatus, procedure, and design. The same turntable apparatus was used as in the previous experiments. The pretests and posttests were identical to those used in the previous experiments, except that for Experiments 4 and 5 facing direction was determined by means of an electronic compass, accurate to 1° . For the rearrangement phase, participants were given much more explicit and detailed instruction about paying attention to how they were moving in the environment (i.e., how they were turning in the room as they stepped around). In addition, they were instructed to test themselves to see how well they could keep track as they stepped (i.e., to actually test themselves on-line by closing their eyes from time to time and guessing what they would be facing when they opened them a few seconds later). Thus, following these attention instructions implicated a component of self-administered error corrective feedback. Error feedback has been found to facilitate adaptation to sensory rearrangement (e.g., Coren, 1966; Welch, 1969). Under such instructions, 8 participants took part in a matched speed condition identical to that of Experiment 2 in which they stepped on the stationary turntable at 10 rpm. Eight other participants took part under the same explicit instructions in a biomechanically faster condition like that of the other experiments, in which they stepped at 10 rpm and turned at 5 rpm.

Results

The overshoot averages are presented in Table 1 (Experiment 4). For the matched speed condition, the overshoot in the same direction and the undershoot in the opposite direction did not differ significantly from zero. For the

biomechanically faster condition, there was a large and significant overshoot in the same-direction measure and no change in the opposite-direction measure. An ANOVA (2 conditions \times 2 test directions) indicated a significant effect of conditions, $F(1, 14) = 12.66, p < .05$, of test direction, $F(1, 14) = 36.45, p < .05$, and of the interaction between condition and test direction, $F(1, 14) = 4.9, p < .05$. The effects for the biomechanically faster condition were greater than those for the matched speed condition, and the same-direction effects were significantly larger than the opposite-direction effects. Individual comparisons indicated that the effects of the biomechanically faster condition were significantly larger than those of the matched speed condition for the same-direction test ($p < .05$) but not for the opposite-direction test ($p > .05$). Individual comparisons also indicated that the effects of the same-direction test were significantly larger than the opposite-direction tests for both the matched speed condition and the biomechanically faster conditions. (However, note that although not significantly different from zero, the pattern of results for the opposite direction test was toward an undershoot in the matched speed condition and there was no effect for the biomechanically faster condition.)

Discussion

In the matched speed condition, if the attentional instructions had a learning effect, it would be to make the participants more accurate and might override sensory adaptation effects or at least reduce them. The magnitude of the overshoot and undershoot in this condition of Experiment 4 was indeed in this direction, in comparison with the comparable matched speed condition of Experiment 2, that is, they were somewhat less but not significantly so, $F(1, 14) = 0.49, p > .05$. The attentional instructions did seem to have an enhancing effect in the same-direction measure of the biomechanically faster condition. This amount of recalibration was larger than in any condition of all the other experiments. It was not clear under the perceptual-learning hypothesis why there was no effect in the opposite-direction measure of this condition. The present learning hypothesis is that there should be overshooting in both directions. It might be reduced by an undershooting effect of a sensory adaptation mechanism. However, the enhancing effect of the instructions seemed to be so strong for the same-direction measure that there should have been some residual overshooting in the opposite direction as well. A replication of this condition in Experiment 5 will help determine whether this was due to random variation or whether it was a reliable experimental result. In addition, in Experiment 5 we introduced another procedure for distinguishing between the possible mechanisms of recalibration.

Experiment 5

In the previous experiments, we used a biomechanically faster condition for the discrepancy between stepping rate and turning rate in the rearrangement phase. As suggested in the hypothesis of two mechanisms, a sensory aftereffect

would summate with a learning mechanism to produce an overshoot when tested in the same direction as the stepping during rearrangement. However, a biomechanically slower discrepancy can also be devised by rotating the turntable in the same direction as the T-bar. Suppose the T-bar was turning clockwise at 10 rpm and the turntable was also turning clockwise but at 5 rpm. A person stepping to hold onto the T-bar would be turning through the environment at 10 rpm but only having to step at 5 rpm to do it.

The perceptual-motor learning component of recalibration should lead a person to undershoot when tested after experiencing such a condition. That is, the person would have learned that little stepping was necessary to cover a large amount of turn. This would mean that the sensory adaptation component and the perceptual-motor learning component would work against each other when tested in the same direction after the rearrangement and would summate in undershooting when tested in the opposite direction.

Method

Participants. Twenty-four undergraduates were paid a nominal sum for their participation in this experiment.

Apparatus, procedure, and design. The same turntable apparatus as in previous experiments was used. The pretests and posttests were identical to that of previous experiments. Three different rearrangement conditions were used: (a) a matched speed condition in which the stepping rate had been reduced to 5 rpm and a turning rate of 5 rpm; (b) a biomechanically faster condition with a stepping rate of 10 rpm and a turning rate of 5 rpm, as in the corresponding condition of Experiment 4; and (c) a biomechanically slower condition, as described earlier, with a stepping rate of 5 rpm and a turning rate of 10 rpm.

Eight participants took part in each rearrangement condition in the usual pretest, rearrangement, and posttest phases. The rearrangement phase for each condition involved stepping in a clockwise direction for half the participants and in a counterclockwise direction for the other half. As usual, testing was done in both directions in the pretest and posttest phases.

The same explicit attention-directing instructions as used in Experiment 4 were given to the participants in all conditions. Again, this was designed to enhance a perceptual-motor learning component of recalibration.

Results

The mean overshoot in degrees for each condition is presented in Table 1 (Experiment 5). It appears from these data that the biomechanically slower condition resulted in a substantial, but statistically nonsignificant, undershoot when tested in the same direction as the stepping during rearrangement. However, in the opposite direction there was a substantial and statistically significant undershoot. It was also the case that the biomechanically faster condition resulted in a substantial overshoot when tested in the same direction but no appreciable change when tested in the opposite direction. The results of the matched speed condition indicate little change in either direction.

The 95% confidence bounds supported this interpretation of the data. It was further supported by a 3 (condition) \times 2

(direction) ANOVA. Here there was a significant condition effect, $F(2, 21) = 10.64, p < .05$, and a significant direction effect, $F(1, 21) = 14.6, p < .05$, that must be interpreted in light of a significant interaction between condition and direction, $F(2, 21) = 10.53, p < .05$. That interaction was due to the large difference for the different directions in the biomechanically faster condition, in contrast to little difference in the other two conditions. Individual comparisons indicated that the difference between the same- and opposite-direction tests was significantly greater for the biomechanically faster condition than for the other two conditions ($p < .05$). The differences between the same- and opposite-direction tests for the matched speed and biomechanically slower conditions did not differ significantly. It was also the case that for the same-direction tests, the biomechanically faster condition differed significantly from the other two conditions, but for the opposite-direction tests, there were no significant differences between conditions. However, note that the only opposite-direction test that differed significantly from zero was in the biomechanically slower condition.

Discussion

The most important result of this experiment was the undershoot in the opposite-direction test as well as the substantial but nonsignificant undershoot in the same-direction test of the biomechanically slower condition. The same direction undershoot provided further support for the perceptual-learning component of recalibration because a sensory adaptation component would work against it. The substantial undershoot in the opposite direction was not so surprising because here the two components would both work to produce an undershoot. Except in Experiment 2, there were statistically nonsignificant changes in the opposite-direction tests of the biomechanically faster conditions, in which the two mechanisms would be working against each other. It may be relevant to note that the magnitude of the undershoot was higher than the undershoot in any of the conditions in all the other experiments.

The large overshoot in the same-direction test of the biomechanically faster condition replicated the finding in this condition of Experiment 4.³ As in Experiment 4, that overshoot did not manifest itself in the opposite-direction test. There was little change in the matched speed condition in either test direction. As previously suggested, in this condition the attentional instructions for enhancing the learning component would tend to reduce any change in calibration. That is, a participant should learn to turn accurately if he or she pays attention to how he or she is moving in the matched speed condition. The slight hint of an overshoot in the same-direction test of this condition might have been due to the sensory adaptation component from the stepping alone.

General Discussion

The several experiments reported here converge on identifying two processes in the recalibration of rotational locomotion, tentatively described as a sensory adaptation compo-

nent and a perceptual-motor learning component. The sensory component was manifest in the matched speed condition of Experiment 2, but it was reduced in that same condition of Experiments 4 and 5, when the participants' attention was explicitly called to how they were moving in the environment. In those cases, of course, there was no discrepancy between their stepping rate and their rate of turning in the world. The perceptual-motor learning component was most clearly manifest in Experiments 3, 4, and 5. In Experiment 3, interlaced clockwise and counterclockwise rearrangement experience gave rise to simultaneous recalibration in the two directions. That result would seem to be incompatible with the type of sensory adaptation process envisioned here, implying the existence of another process. In Experiments 4 and 5, an attentional manipulation was introduced to enhance the learning component of recalibration. This seemed to work in both experiments, particularly in the biomechanically faster condition, when recalibration was measured in the same direction as the stepping in the rearrangement condition. Attentional manipulations have been found to affect adaptation to displacing prisms (e.g., Canon, 1971; Kelso, Cook, Olson, & Epstein, 1975). However, these effects are not manifest in the amount of adaptation but in the nature of the adaptation, depending on what sense modality is attended to.

Qualitatively, the general pattern in the evidence just summarized seems convincing in support of the idea of two components involved in recalibration. However, quantitatively, the pattern lacks precision, even beyond the previously noted variability in the degree of recalibration in the biomechanically faster condition. Most specifically, the hypothesis being proposed is that (a) the sensory adaptation component involves a dimensional shift, which means that an overshoot in one direction should be accompanied by an undershoot in the opposite direction; (b) the perceptual-motor learning component involves an appreciation of general perception-action relations, such that overshooting in one direction should be accompanied by overshooting in the opposite direction; and (c) these two different components would combine algebraically.

Presumably, as noted, without any specific attention-enhancing instructions, as was the case in Experiment 1,

³ The overshoot found in the biomechanically faster condition (the same-direction test) of Experiment 1 was also large, 92.1°. However, most overshoots in that condition without the special attention-enhancing instructions have been considerably less: 28.8° in Rieser et al. (1995), 33.5° in Experiment 2 of the present research, and 61.2° in Experiment 3. The overshoots found in these three experiments of the present research in this condition were statistically significantly different, $F(2, 20) = 3.94, p < .05$. Comparisons between pairs of means indicated that a mean of 92.1° in Experiment 1 was significantly greater than the 33.5° of Experiment 2. No other difference reached statistical significance. We do not know why the results varied so much between experiments. Participants might have differed in how much attention they spontaneously paid to the perceptual-motor correlation. Alternatively, the experimenters might have differed in how much verbal emphasis they placed on paying attention to one's surroundings when reading the instructions.

sensory adaptation occurs, as does perceptual-motor learning depending on how naturally observant the participants are. Thus, the posttest results are a combination of these two components. The results of Experiment 1 here show a substantial predicted overshoot in the same-direction posttest and a small and statistically insignificant overshoot in the opposite-direction test. The small opposite-direction overshoot was obtained in several unreported replications of this experiment. It is possible that this small effect was the result of a sensory adaptation undershoot almost neutralizing a perceptual-motor learning overshoot. This was supported by the almost-equal same-direction overshoot and opposite-direction undershoot in the matched speed condition of Experiment 2. In the biomechanically faster condition of that same experiment, the overshoot in the same direction was slightly higher than the overshoot in the matched speed condition (43.9° as opposed to 33.5°). This is in accord with the hypothesis, assuming that the biomechanically faster condition includes both a sensory adaptation and a learning component in the recalibration effect. However, in the opposite-direction test of Experiment 2, the undershoot for the biomechanically faster condition was approximately the same as for the matched speed condition (-29.7° and -24.8° , respectively). The hypothesis predicts that the undershoot in the opposite-direction test of the biomechanically faster condition would be substantially less than that in the matched speed condition. In the biomechanically faster condition, the sensory adaptation undershoot in the opposite direction should be greatly reduced by the perceptual-motor overshoot in that direction.

As another example of the hypothesis not fitting quantitatively, consider Experiment 4, in which the attention-directing instructions were introduced. In accord with the hypothesis, in the matched speed condition the sensory adaptation effect seemed to be reduced, as would be expected with enhanced attention to the nondiscrepancy, making participants generally more accurate. Furthermore, there was a large enhancement (98°) in the same-direction test of the biomechanically faster condition, again presumably due to the attention enhancement. However, that enhancement only neutralized but did not reverse the sensory adaptation effect in the opposite direction test (-21.6° vs. 1.4°).

The lack of a quantitative fit may just have been due to the noisiness of the data. Both the within- and between-subjects variability was high. Alternatively, it could be that the parts of the hypothesis concerning the generalization or transfer of the components from same to opposite side are not correct. In particular, if it were assumed that the perceptual-learning component only transferred partially from stepping in the same direction to stepping in the opposite direction, a number of the above discrepancies would disappear or be reduced. However, this is an ad hoc, not a principled, modification of the hypothesis. There may be ways to reduce the variability of the results, and this would not only serve to investigate whether that is the cause of the lack of precision but it would also make it easier to verify whether the partial transfer hypothesis were correct. It is, of course, also possible that the hypothesis of transfer to the opposite side for the perceptual-learning component of recalibration is

simply wrong. There is considerable evidence in the literature on adaptation to sensorimotor rearrangement for context-specific recalibration effects (e.g., Shelhamer, Robinson, & Tan, 1992; Welch, 1978, pp. 96–101). However, in much of this research, direct experience with the context specificity is provided. For example, Shelhamer et al. provided participants with alternate exposure to conditions driving vestibular-ocular reflex gain in different directions when they were looking up and looking down. In posttests, different after-effects were found depending on the direction of gaze. This is analogous to the bidirectional effects of Experiment 3 of the present research. In our other experiments, in the rearrangement conditions participants experienced the perceptual-motor discrepancy in only one context. The present hypothesis is that transfer to other contexts provides a way of determining the organization of the perceptual-motor systems.

Whatever the explanation for lack of quantitative precision, there are a number of issues arising from the present results. One concerns organization of perceptual-motor coordination. Rieser et al. (1995) proposed that the pattern of transfer of recalibration from task to task was a window into the organization of coordination. In that study, they found that recalibration of linear locomotion transferred from one speed of locomotion to another and from one gait to another, but not from walking to throwing or from linear locomotion to turning. They conjectured there that the organization as indexed by transfer or generalization was based on a functional principle. Thus, any tasks that involved translatory locomotion would exhibit transfer, any that involved throwing or hurling would exhibit transfer, any that involved rotary locomotion would exhibit transfer, and so on. Thus, the hypothesis is that recalibration of translatory walking in the form of overshooting or undershooting would transfer to wheeling in a wheelchair, recalibration of throwing would transfer to kicking of a soccer ball, and so on. Relating the present two-component results to that conjecture, it would not be expected that the sensory adaptation component would exhibit transfer if a different limb and muscle system were being used. Our view is that the sensory adaptation component of recalibration is due to a biomechanical mechanism (e.g., adaptation of joint receptors) rather than vestibular adaptation. Thus, suppose that rotary locomotion of stepping were recalibrated as in the above experiments. If tests were then made on a turntable in which participants pulled themselves around by hand, it would not be expected that the sensory adaptation component would transfer because that component is hypothesized to be related to activity of the legs in stepping. In any case, the functionally based perceptual-learning component would be expected to transfer.

A second issue that is raised by the present results also relates to the previous work on recalibration of translatory locomotion by Rieser et al. (1995). There was no evidence for a sensory adaptation component in the case of recalibration of translatory locomotion. In that study, neither a matched speed condition nor walking without vision resulted in any recalibration. Of course, in the present research, a matched speed condition did produce recalibra-

tion effects, and in a study by Wagner (1996) rotational locomotion with closed eyes also resulted in recalibration. In neither of those cases could the recalibration be based on perceptual learning.

Exactly what might be the nature of this sensory adaptation component of the recalibration? As noted above and in the discussion of the results of Experiment 1, this component might involve some kind of biomechanical feature detector, perhaps adaptation of joint receptors. However, the experiments here do not rule out some sort of vestibular adaptation consequent on prolonged turning in one direction during the rearrangement experience. An experiment by Gordon, Fletcher, Melvill Jones, and Block (1995) may be relevant. Their participants walked on the periphery of a rotating disk at such a speed that they remained stationary "relative to space and the visual surround" (Gordon et al., 1995, p. 540). After 2 hr of such stepping experience, they were asked to walk a straight line in an open space with closed eyes. All participants showed an aftereffect while trying to walk straight, of turning in the same direction as their stepping motion on the disk. In a companion task of the same sort but wheeling in a wheelchair, no such aftereffects were observed. Because there was no actual turning in space during the disk experience, these results suggest that there is a nonvestibular mechanism for one kind of rotational recalibration. Although the stepping action in the study by Gordon et al. and the present research are different in the nature of the aftereffect, they may nevertheless reflect the same type of adaptation.

This still leaves open the question of why there should be a sensory adaptation component in the recalibration of rotational locomotion but not in the case of translatory locomotion. Perhaps there is a dimensional character to rotational locomotion ranging from clockwise turning to counterclockwise turning in a way that does not exist for translatory locomotion. The analog for translatory locomotion would be stepping forward and stepping backward, but these may be qualitatively different movements rather than dimensional.

A final issue related to the possible dimensional character of locomotion concerns limits or constraints on what kinds of recalibration are possible. In the present experiments, rotational recalibration was demonstrated with biomechanically faster and slower rearrangements. However, in both of these cases, the direction of stepping and turning in the world was the same. Thus, if one were stepping clockwise, one would be turning through the world clockwise as well, albeit at a slower or faster rate. On the other hand, it would be possible to arrange (rearrange) the locomotion so that as one stepped clockwise, the movement through the world would be counterclockwise. If rotational locomotion were simply a dimensional action, then recalibration might occur in this condition. During the posttest a participant could be asked to look at a target 90° to the left, close his or her eyes, and turn to face it. The prediction would be that they would turn to the right. The analogous situation for translatory locomotion would be stepping forward to move backward. These are unusual predictions but would be strong tests of the kind of model under consideration here.

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