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Calibration of Human Locomotion and Models of Perceptual-Motor Organization

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People coordinate the force and direction of skilled actions with target locations and adjust the calibrations to compensate for changing circumstances. Are the adjustments globally organized (adjusting a particular action to fit a particular circumstance would generalize to all actions in the same circumstance); anatomically specific (every effector is adjusted independently of others); or functional (adjustments would generalize to all actions serving the same goal and generating the same perceptible consequences)? Across 10 experiments, changes in the calibration of walking, throwing, and turning-in-place were induced, and generalization of changes in calibration to functionally related and unrelated actions were tested. The experiments demonstrate that humans rapidly adjust the calibration of their walking, turning, and throwing to changing circumstances, and a functional model of perceptual-motor organization is suggested.

People coordinate skilled actions to fit the distances and directions of objects in their surroundings. For example, in the woods the force of a backpacker's jump fits the distance across a stream; on a playing field the force, timing, and direction of a quarterback's throw fits the receiver's trajectory; and in an auditorium the loudness of a lecturer's speaking fits the distance to the audience. Such examples make it clear that perceptual and motor systems are mutually calibrated—after seeing the relevant distances, the backpacker knows how hard to jump, the quarterback how hard to throw, and the speaker how loudly to talk.

But skilled actions could not reflect a single, fixed set of calibrations serving to map target locations into one-to-one correspondence with actions, because the needed force and direction of action depend on temporary variations in the situation. For example, the distance across a particular stream may be constant, but the force of jump depends on the backpacker's load and footing as well as the distance; the needed force and direction of throw depend on the force and direction of the wind; and the needed loudness of public speaking depends on the room's acoustics and ambient noise level. Skillful actions are tuned to changes in circumstances. But as rueful backpackers, quarterbacks, and lecturers know, adjusting calibrations to fit with changing circumstances requires practice to fine-tune actions to the changes. How are such changing calibrations organized? To what degree does fine-tuning a particular action to fit a particular situation serve to fine-tune other actions to fit the same situation? Alternatively, to what degree must each action be fine-tuned independently to fit the same situation?

As an example, consider the effects of a gale-force head-wind or tail-wind on a backpacker facing a stream, who wishes to shout to her companions on the other side of the stream, throw her backpack across to them, and then jump the stream herself. More force of shouting, throwing, and jumping would be needed to act against the wind and less force to act with it. At one extreme, the calibrations for different actions affected by the wind might be highly interrelated and unified. If such a "global" organization is the case, then practice fine-tuning the force of jump, for example, would generalize to all actions influenced by the wind (e.g., in throwing and shouting that were fine-tuned to fit the situation as well). At the other extreme, the calibrations for different effectors might be independent. If such an "anatomically specific" organization involving different effectors is the case, then practice with a constant head-wind to fine-tune the force of jump across a particular stream would not generalize to different actions (like throwing or shouting), to different gaits (like jumping from a running start or from a standstill), nor even to jumping streams of different widths in the same head-wind.

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Neither extreme seems plausible, given their respective costs and benefits in terms of the efficiency of adaptive behavior on the one hand or of the underlying structures on the other. A global organization would be behaviorally adaptive, because practice fine-tuning one action to fit a given situation would result in all actions being fine-tuned. But we suppose it would be structurally costly to unify the fine-tuning of all actions and particularly inefficient in situations where only one action is needed. Conversely, an anatomically specific organization of particular effectors might be easier to engineer structurally but would be less behaviorally adaptive. There are myriad intermediate models, trading off different behavioral and structural costs in different ways; many are plausible, but in the absence of relevant data, the choice of one instead of others seems arbitrary. The exception to this is a functional organization. If the calibrations are functionally organized, then practice fine-tuning one action would generalize to other actions designed to accomplish the same goal. Such an organization would be adaptive, tuning all alternative methods of achieving a goal at once to meet the demands of the changing situations. Consider the implications of a functional organization for jumping, throwing, and shouting when facing a strong head-wind. Practice fine-tuning any one of these three actions would not generalize to any of the others. But practice jumping would generalize to all forms of hurdling an obstacle (e.g., jumping with a running start or from a standstill and one-legged or two-legged jumping), and it would generalize to streams of different widths. Practice throwing an object through space would generalize to different distances of throw and would generalize to different forms of throwing (e.g., underhanded or overhanded) and to kicking as well. And finally, practice shouting would generalize to other forms of communicating (e.g., clapping and whistling), and it would also generalize to different distances.

We report 10 experiments about the calibration of perception and action. We contrived situations requiring a change in calibration and provided participants with the chance to practice a particular action in the contrived situation. To find out whether the participants adjusted the calibration of the practiced action, we compared performance on pretests without feedback (before the chance to practice with feedback in the contrived situation) with performance on posttests without feedback. To find out about the organization of the changing calibrations, we assessed patterns of generalization, sometimes to actions from the same functional category and sometimes to actions from different categories.

Forward walking was the main behavior used to investigate perceptual–motor calibration. With vision, people might spot obstacles and set a ballistic course around them, reflecting the calibration of their walking against their visible surroundings. In addition, though, they probably use ongoing feedback, making it difficult to investigate the calibration implied by ballistic course-setting when people walk with vision. To investigate the calibration implied by ballistic course setting, participants were asked to view a target object and then close their eyes and attempt to walk to its remembered location without feedback. The organization of the changes in the calibration of forward walking was probed by testing for generalization of the changes to three other actions. One was side-stepping, where participants looked at a target, closed their eyes, and then attempted to side-step without feedback to its remembered location. Like forward walking, side-stepping is produced by the legs, serves the functional goal of changing observation point, and results in a visible translation in perspective, but it differs in how the legs are used (gait). A second was turning in place, where participants looked at a target, closed their eyes, and attempted to turn in place in order to face its remembered location again. Like forward walking, it is produced by the legs. But it serves the different functional goal of changing heading, and it differs in gait. And the third was throwing, where participants looked at a target, closed their eyes, and attempted to throw a bean bag so it would land in the target's remembered location. Like the forward walking, the throwing was aimed at remembered targets and performed without feedback, but it served the different goal of launching an object to a new location; resulted in visible trajectories; and was produced by the arms, not the legs. The functional model underlying the generalization experiments emphasizes the perceptible, short-term consequences of actions moving to a new observation point, turning to a new heading, and launching an object to reach a new location.

Walking Without Vision and Other Methods to Probe Perceptual-Motor Calibration

People can view a target in an open field, close their eyes, and walk to it accurately. That children can do this is widely known from watching children's games, like pin-the-tail-on-the-donkey. The skill has been investigated experimentally as well (e.g., Elliott, 1987; Loomis, DaSilva, Fujita, & Fukusima, 1992; Rieser, Ashmead, Talor, & Youngquist, 1990; Steenuis & Goodale, 1988; Thomson, 1983). For example, Rieser et al. (1990) asked adults standing in an open field to view a target located 2 to 22 m straight ahead and attempt to walk to its position without vision or other sources of feedback. Their variable errors averaged about 8% of the target distance, and the constant errors averaged about 2%. Even when attempting to walk to the 22 m target, participants stopped within 1.5 m of it on most trials.

How might they have known how far to walk? For sighted people, the activities of walking typically provide optical flow stimulation, which (sometimes in combination with the flow of sounds, wind, and heat) specifies their changing directions and distances relative to features of their visible surroundings. We suppose that when walking with vision, people register the covariation of the flow of their biomechanical activity and the resulting optical flow; in other words, they learn about the visible (and other) consequences of their biomechanical activities. Then when walking without vision, they act on this learned covariation. Such a "learned covariation" hypothesis implies a flexible system, because the relation between biomechanical activity and the resulting changes in perspective varies with growth. Additionally, it changes with tool-use (e.g., roller skates and skis extend one's glide) and with situation (e.g., walking with the wind or against it, walking uphill or downhill).

Our approach exploits what we assume to be the perceptual-motor system's flexibility, by asking people to walk in situations where the relative rates of biomechanical activity and environmental flow are artificially changed. Artificial changes like this occur whenever one walks while underway on ship, train, or the beltways used to assist people moving between airport terminals. Changes like this occur naturally as well, for example, when swimming against a current and walking on soft or slippery ground. In the present experiments, the change was created by having participants walk at one speed on a motor-driven treadmill (causing a given rate of biomechanical activity) while the treadmill was towed through the environment at a different speed (providing a different rate of environmental-flow information) as depicted in Figure 1. Before and after this experience, participants were asked to look at a target, close their eyes, and walk to the target's location. When the rearrangement involves walking at a faster speed on the treadmill than is specified by the environmental flow (because the treadmill is set at a fast pace while it is towed slowly through the surroundings), the posttest should result in walking too far relative to the pretest. Conversely, when the rearrangement involves walking at a slow speed on the treadmill while being towed rapidly through the surroundings, the posttest should result in walking too short relative to the pretest.

The present experiments were conducted in the tradition of the classical rearrangement studies conducted in the middle of the 19th century, which were discussed by Helmholtz (1962). A variety of optical devices were used in the early studies to induce radical optical changes, for example, inverting and left–right reversing the retinal image. The early researchers assumed that adult adaptability to such rearrangements would shed light on the degree to which perceptual development and perceptual-motor development depended on experience (e.g., Kohler, 1955; Snyder & Pronko, 1952; Stratton, 1896).

Around 1960 rearrangement studies shifted toward the use of prisms to understand perceptual-motor coordination (Harris, 1965; Held, 1962) and the organization of coordination (Held & Mikaelian, 1964; Pick, 1970). The present approach is most similar methodologically to that of Harris (1965), Hay and Pick (1966), and recently Bedford (1993) in producing a change in perceptual-motor coordination and then using a variety of generalization tests to infer the organization of that coordination. But the present experiments differ from the earlier traditions in two important ways. First, they are focused on dynamic spatial orientation, changing distances, and the calibration of locomotion, whereas the earlier ones were focused either on static visual perception or on the calibration of reaching and azimuth perception. And second, in the present experiments changes in calibration were exploited systematically to probe the nature of perceptual-motor organization through patterns of generalization across different actions.

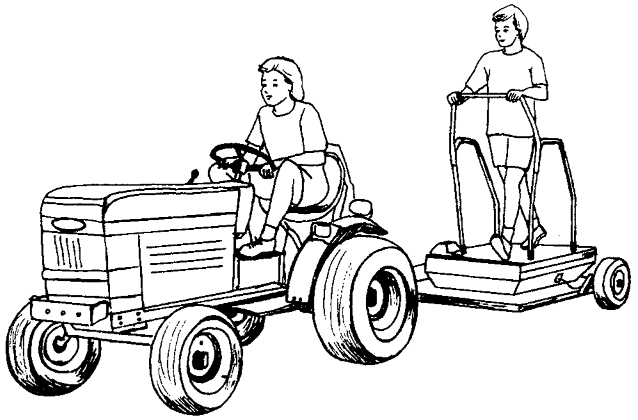

Figure 1. Drawing of the treadmill towed behind a tractor on a low trailer. It was used to induce change in the calibration of forward walking.

What Is Already Known About the Calibration of Human Locomotion?

There are many studies about the perception of locomotion but not about its calibration. Some are studies of sensitivity to optical flow per se, in which participants viewed an optical flow field from a stationary position and judged the direction or rate of self-movement that was specified by the flow (e.g., see Cutting, 1986; Gibson, 1958; Warren & Wertheim, 1990). Some are studies of sensitivity to vestibular input per se (e.g., Guendry, 1974), and a few are studies of sensitivity to biomechanical input per se (e.g., Bles, 1981). Finally, some are studies in which rates of self-movement were assessed in conflict situations, where participants experienced discrepant rates of optical flow and of biomechanical activity (Fluckiger & Baumberger, 1988; Lackner, 1985; Laurent, Paul, & Cavallo, 1988).

Lee and his colleagues have focused directly on how optical flow is used to guide locomotion in their studies of how time-to-contact (the visual angle subtended by a particular feature divided by its rate of change) is used to control the timing of the take-off point in broad-jumping (Lee, Lishman, & Thomson, 1982) and the timing of vertical jumping to punch a falling ball (Lee, 1980). For example, in a study of running in a simulated "broken field" situation, Warren, Young, and Lee (1986) asked participants to run on a treadmill and to vary their stride length so that their feet fell on targets that were irregularly spaced along the treadmill's moving belt. As their research and that of others (Patla, Prentice, Robinson, & Neufeld, 1991) showed, skillful runners can accomplish this by varying each step's vertical impulse, horizontal impulse, and delay until the next step. The predominant strategy was maintaining a constant horizontal impulse (and therefore constant rate of forward motion) while varying the vertical impulse from step to step. Steps with greater vertical impulse result in longer stride lengths; those with softer impulses, in shorter stride lengths. How do skillful runners know how much vertical impulse is needed to reach a target displaced by a given distance along the ground? Skillful running like this involves the calibration of vertical impulses against horizontal distances.

Overview of Experiments 1–5: Demonstration of Changes in Calibration and the Perceptual-Learning Processes That Underlie Them

The first five experiments were focused on basic processes of change in the calibration of forward walking, not on the generalization across actions. The purpose of Experiment 1 was to determine whether walking changes calibration after people experience a new relation between their rate of biomechanical activity relative to the rate of movement through the surroundings. In one condition, the biomechanical rate of walking was increased relative to the environmental-flow rate; participants were predicted to overshoot the target during the posttests. In the other condition, the biomechanical rate of walking was decreased relative to the environmental-flow rate; participants were predicted to undershoot the target during the posttests.

The purpose of Experiment 2 was to evaluate whether the errors observed in Experiment 1 might be due, in part, to a simple aftereffect of the biomechanical activity of walking on the treadmill. Experiment 3 was designed to evaluate whether errors might be due, in part, to a simple aftereffect of the environmental flow specifying their rates of movement relative to the surroundings while being towed on a trailer. Experiment 4 was designed to evaluate whether the Experiment 1 errors might be due, in part, to the discrepant eye heights when walking on the treadmill versus walking during the pretest and posttest trials. And finally, Experiment 5 was designed to determine which features of the forward-walking gait were changed and reflected in the new calibration.

Experiment 1: Demonstration of Changes in the Calibration of Locomotion

Method

Participants, test space, and equipment. The participants were 8 university staff members who were unaware of the issues motivating the research. The test space was a large, open, asphalt parking lot that was 75 × 120 m in size. An office building framed one side of its perimeter, streets lined sparsely with shrubs framed two sides, and densely packed trees and shrubs framed the fourth side. There were white lines on the ground to demarcate parking spaces. To present the rearrangement conditions, a motor-driven treadmill of 30 cm in height was mounted atop a trailer 45 cm high and towed 2 m behind a subcompact automobile. (Tractors were used in later experiments, as shown in Figure 1.)

Before the tests, participants were equipped with a blindfold; they rested it on their foreheads when looking at the target and lowered it to cover their eyes immediately before attempting to walk to the target. In addition, participants were equipped with a sound system so they could not localize ambient sounds that might have served as auditory landmarks to guide their walking. The sound system consisted of a headset connected to a short-range FM receiver; the tester was equipped with a microphone and FM transmitter. The receiver's gain was set so that participants could not localize sounds during the tests (the loudness was about 75 dB SPL), although they could readily hear the tester's verbal instructions.

Design and procedures. A pretest–intervention–posttest design was used. The procedures occurred in five phases: warm-up, pretest, rearrangement, posttest, and debriefing, in that order. During the warm-up phase, participants were asked to practice walking without vision on their own for 2 to 3 min in order to build their confidence that they could travel safely and accurately when walking without vision. To practice on their own, they were asked to pick a spot on the ground as a target, close their eyes, attempt to walk to the remembered spot, and then look for feedback after each attempt.

Pretest and posttest trials were devised to assess how accurately participants could look at a target and then walk straight ahead to its remembered position without information from their surroundings. For the pretests, eight repeated trials were used to provide a stable baseline of performance. For the posttests, eight repeated trials were also used, to see how long the expected recalibration effects lasted. The methods for the pretest trials and the posttest trials were exactly the same.

The tests were conducted near the middle of the parking lot. A cloth measuring tape started at the participant's feet and stretched straight ahead of the participant along the ground for 16 m. There were two testers—one served as the target person and data recorder and the other as the sighted guide. The target-tester stood 8 m straight ahead of the participant. Participants were asked to study the tester's position, pull down the blindfold, and attempt to walk to the tester's position. As soon as the participant started to move, the tester moved 5 or 6 m to the side so the path would be clear; the participants knew that the tester would get out of the way. The tester wrote the distance of the stopping point, recorded by reading the location of the participant's left foot on the measuring tape. Participants typically veered a bit away from the tape, in which case the data recorder simply read by line-of-sight the left foot's projection to the tape. For 94% of the trials, participants veered by less than 1 m. The sighted guide tester followed 3 or 4 m behind the participant. After the response was recorded, participants grasped the tester's upper arm and were guided back to the starting position, following sighted guide techniques devised for persons who are blind (Hill & Ponder, 1976). The participants had no information about the accuracy of their performance.

It is important to note three additional features of the procedure. First, the starting point was varied from trial to trial so that there were no consistent irregularities in the surface texture that could have served as landmarks. Second, participants were asked to respond by keeping the target in mind while they walked and to avoid using other strategies. Because some participants in earlier studies said they sometimes counted steps or seconds as a method of keeping track of how far they had walked without vision (Rieser et al., 1990), participants were asked not to count in the present experiment. Third, participants were asked to suppose they had erred (either a little or a lot) after each set of test trials and to guess whether they tended to err by walking too far or too short a distance.

During the rearrangement phase, participants were asked to pay attention to their surroundings as they walked atop the treadmill at one speed while being towed through the surroundings at a different speed. This lasted 8 min for each of two conditions. In the biomechanically faster condition, the treadmill operated at 8 kph and the trailer was towed at an average speed of 5 kph; although the treadmill's speed was constant, the car's speed varied whenever it went up or down the slight grade of the parking lot. In the biomechanically slower condition, the treadmill operated at 7 kph and the car averaged 17 kph.

After the posttests, participants were asked in the debriefing phase to describe how they knew where and when to stop while walking without vision during the tests, whether they kept the target position in mind while they walked, and whether they had images of other features of the surroundings in mind as well.

Results

Evidence of a change in calibration would be reflected in a change in the distance walked from the pretests to the posttests. To obtain a reliable estimate of each participant's pretest walking distance, a single pretest score was computed for each individual by averaging the distances walked across the eight repeated pretest trials. Two scores were computed to characterize change in calibration. One was the error on the first posttest trial, computed by subtracting the first posttest error from the averaged pretest error scores. If the change in calibration is short-lived, then this "first-trial error" would be the best single measure of the predicted changes. The other was the posttest errors averaged across the eight repeated trials, computed by subtracting the averaged posttest error from the averaged pretest error scores. If the change in calibration is relatively long-lived, then this "repeated-trials error" should provide a reliable estimate of the change.

The average first-trial errors appear in Figure 2. As predicted, all 4 participants in the biomechanically faster condition walked past the target during the posttests, and all 4 participants in the biomechanically slower condition stopped short of the target. These effects were statistically significant for both the first-trial errors and for the repeated-trials errors. In the biomechanically faster condition, the first-trial errors showed participants had walked an average of 18% (*SD* = 8) further on the posttests than on the pretests, $t(3) = 4.51$, $p < .05$; the repeated-trials errors significantly differed as well, $t(3) = 14.3$, $p < .05$. In the biomechanically slower condition, the first-trial posttest errors were significantly shorter than the pretest errors. Errors averaged 7% (*SD* = 2) less than the pretest distance, $t(3) = 7.01$, $p < .05$; the repeated-trials errors averaged 8% (*SD* = 2) less than the target distance, $t(3) = 3.50$, $p < .05$. An unexpected finding was that participants in the biomechanically faster condition erred by a larger absolute distance than did participants in the biomechanically slower condition, $t(6) = 6.01$, $p < .05$.

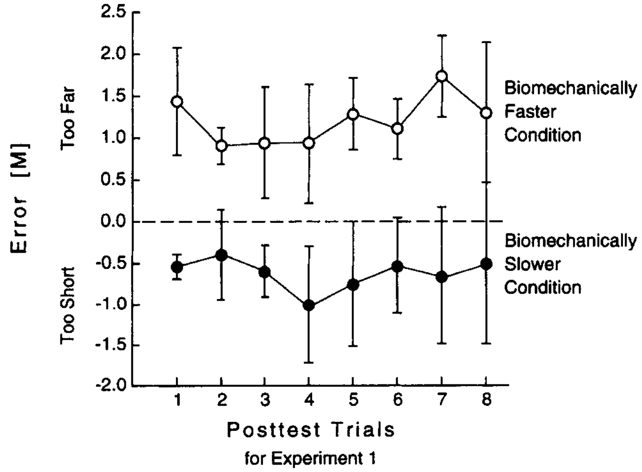

Figure 2. The average errors as a percentage of target distance from Experiment 1 for the biomechanically faster (top panel) and biomechanically slower (bottom panel) conditions. The bars indicate the size of one standard deviation.

Discussion

The participants were not aware that they had erred during the posttest trials and when forced to guess whether they had tended to walk too far or stop short during the posttests, only 1 of the 8 guessed correctly. For the posttests, after the biomechanically faster condition, when participants actually walked too far, they felt as if they might have stopped short of the target; for the posttests after the biomechanically slower condition, when participants actually walked too short a distance, they felt as if they might have walked too far. When walking without vision, participants perceived themselves as traveling through their remembered surroundings at a slower rate (after the biomechanically faster condition) or at a faster rate (after the biomechanically slower condition) than they had actually traveled. The change in perceived walking rate reflects change in the calibration of biomechanical activity relative to distances in the remembered surroundings. Our hypothesis is that these changes in the calibration of walking were responsive, in turn, to the changes in the rate of biomechanical activity relative to the rate of environmental flow experienced during the rearrangement phase.

An alternative hypothesis is that the errors may reflect simple sensory aftereffects alone, not a change in calibration due to the discrepant rates. For example, the posttest errors may reflect a simple aftereffect from the environmental-flow information while being towed behind the car or may reflect the biomechanical activity while walking on a treadmill. This is easily ruled out because the participants walked too far in the one condition and stopped short in the other condition, whereas the result of a simple aftereffect would cause the same direction of error after both conditions.

The errors reflecting the change in calibration were asymmetrical, significantly greater in magnitude after the biomechanically faster condition than the biomechanically slower condition. We are not aware of a reason to suppose that the discrepant rates during the rearrangement phase would lead to such asymmetrical changes. Consider three possible explanations. First, the asymmetrical errors may indicate an additional process, one inducing participants to walk farther than they otherwise would in both conditions, therefore adding to the error after the biomechanically faster condition and subtracting from it after the biomechanically slower condition. Second, the asymmetrical errors may reflect a feature of our methods, namely, that the treadmill and towing speeds differed by a greater amount in the biomechanically slower condition (17 kph and 7 kph) than in the biomechanically faster condition (5 kph and 8 kph). Third, the asymmetrical errors may reflect a mathematical difference in the distributions, due to the nature of the different errors we wished to investigate. The maximum possible error when walking too long a distance was unconstrained in this situation, and participants' errors could freely range upward from zero. The maximum possible error when walking too short a distance, on the other hand, was bounded by the target distance itself. Experiments 2, 3, and 4 were designed to help evaluate these alternatives.

Experiment 2: Is the Asymmetrical Change in Calibration Due to an Additional Effect of Biomechanical Activity Alone?

Experiment 2 was designed to test whether the asymmetrical size of the change in calibration might indicate that there was an error due to the biomechanical activity alone while walking on the treadmill that added to the error due to the discrepant rates of biomechanical activity and environmental flow. Participants were pretested and posttested as before—by viewing a target, closing their eyes, and attempting to walk to the target's location. In between the test phases they were asked to walk on a motor-driven treadmill that was not being towed, with their eyes open in one condition and closed in the other. If there was an aftereffect of the biomechanical activity alone while walking on a treadmill, then participants should tend to overshoot during the posttests after the eyes-closed condition; if there is not an aftereffect, then they should not make any systematic errors. The eyes-open condition represents a limiting case where one might expect a change in the calibration of forward-walking—the limiting case of environmental flow specifying forward movement (that is, zero net translatory flow) paired with walking activity. If calibration changes in such limiting cases, then participants should tend to walk too far in the posttests relative to the pretests. In the eyes-closed condition, on the other hand, the walking activity was the same, but it was not paired with environmental-flow information. The conditions were conducted indoors and on a stationary treadmill for convenience and because of the rainy season.

Method

Six adults served as participants. The tests were conducted in a basement corridor 36 m long. The procedures were closely modeled after those used in Experiment 1. During the pretest and posttests, participants were asked to walk to an 8-m target on six repeated trials. There were two rearrangement conditions, and in both, participants walked for 10 min at 4 kph on the treadmill, which was fixed in place on the floor. In one condition, participants walked with their eyes open on the treadmill, and in the other they walked with their eyes closed. Half of the participants were in the eyes-open condition first, and the others were in the eyes-closed condition first.

Results and Discussion

After walking on the treadmill with their eyes open, participants tended to walk too far during the posttests, whereas after walking on it with their eyes closed, they did not err in any consistent direction. In the eyes-open condition, the first-trial errors showed participants had walked on average 10% (SD = 3) further on the first posttest than on the pretests, $t(5) = 3.99$, $p < .05$; the repeated-trials errors averaged 11% (SD = 3) and significantly differed as well, $t(5) = 8.40$, $p < .05$. In the eyes-closed condition, on the other hand, the first-trial errors averaged 3% (SD = 8), and the first-trial posttest errors did not significantly differ from those in the pretests, $t(5) = .81$. The repeated-trials errors also averaged 3% (SD = 7), and the posttests did not significantly differ from the pretests.

The results in the eyes-open condition indicate there was a change in calibration even in the limiting case of no net translatory environmental flow. But the results do not show an aftereffect of the biomechanical activity per se on the posttests, and thus the asymmetrical errors in Experiment 1 are unlikely to be due to the biomechanical activity alone. Experiment 3 was designed to assess whether the asymmetry resulted from the environmental-flow experienced while being towed on the trailer.

Experiment 3: Is the Asymmetrical Change in Calibration Due to an Additional Effect of Environmental Flow?

Participants experienced the flow of sights, sounds, and wind while being towed on the trailer. It might be that there is a sensory aftereffect of environmental flow per se that accounts for the asymmetrical errors, by inducing participants to walk too far, thus adding to the error due to the change in calibration induced during the biomechanically faster condition and subtracting from the change induced during the biomechanically slower condition. Experiment 3 was designed to evaluate this.

Method

Six graduate students served as participants. There were six pretest and six posttest trials, all conducted as in the other experiments. The rearrangement was the limiting case where participants stood without walking atop the stationary treadmill while it was towed at 5 kph for 10 min.

Results and Discussion

There was no systematic effect on the posttests of the flow of environmental information after participants had been passively towed behind the tractor while standing on the stationary treadmill. On the first posttest trials, participants tended to walk too short a distance, whereas on the latter trials they tended to walk too far. The first-trial errors averaged −3% (SD = 7), showing that participants had tended to walk a slightly shorter distance during the pretest trials than the posttest trials; the two did not significantly differ, $t(5) = .10$. Opposite to the first-trial errors, the repeated-trial errors averaged 9% ($SD = 7$), showing that participants had tended to walk further during the posttest trials than the pretest trials, $t(5) = 3.10, p < .05$.

Experiment 4: Is the Asymmetrical Change in Calibration Due to the Discrepant Eye Heights from the Rearrangement Phase to the Posttest Phase?

Participants walked at an elevated eye height while on the treadmill during the rearrangement phase, whereas they stood at their normal, anatomically correct eye heights during the test phases. This discrepancy in eye height may have induced a change in calibration in walking without vision relative to remembered targets, and the effect of this change may have summed with the effect due to the discrepant rates. Following a lead established by James Gibson (1958, 1979), others have proposed that visible distances are perceived and calibrated in terms of units defined by features of the body or of action (Hofsten & Lee, in press; Lee, 1980). To relate this to the present task, consider that during the rearrangement phase participants walked on the treadmill at an elevated eye height, whereas during the posttests they viewed the targets from their actual anatomical eye height. Logically, the discrepant eye heights across the rearrangement phase and the posttest phase could induce a recalibration.

This possibility depends on two assumptions. One assumption is that when walking with vision, people tend to perceive walking rate in eye-height units; it follows from this that during the rearrangement phase, participants would perceive their walking rate in elevated eye-height units. The second assumption is that people tend to perceive distances in eye height units; it follows from this that when viewing the targets during the test trials, participants would perceive target distances in anatomical eye-height units. Then participants would have calibrated their rate of biomechanical activity while walking on the treadmill in elevated eye-heights units, whereas they would have calibrated the self-to-target distances during the tests in the smaller, anatomical eye heights. This would have induced them to walk too far after the biomechanically faster and after the biomechanically slower conditions alike; and summed with the recalibration effects due to discrepant rates in the two conditions, it would account for the asymmetrical pattern of errors. However, it would not have induced walking too far after being passively towed in Experiment 3; although the participants experienced the flow of their surroundings from an elevated eye height, they were standing still so the flow did not covary with their action. Experiment 4 was designed to test for change in calibration due to the discrepant eye heights.

Method

The eight repeated pretest and posttest trials were exactly the same as in the earlier experiments. However, there were differences in the equipment used, in the constancy of the speeds experienced during the rearrangement phase, and in one of the rearrangement conditions. One rearrangement was a biomechanically faster condition, in which participants walked on the treadmill at a rate of 8 kph while being towed 4 kph through the environment. The other was a matched-speed condition, in which participants walked on the treadmill at 8 kph while being towed at 8 kph through the environment. For the Matched Speed Condition it was critical that the rates of biomechanical activity and environmental flow were constant and exactly matched. A high-torque tractor was used to tow the trailer and treadmill during the rearrangement phase, so the towing speed was reasonably constant. The speeds of the treadmill and tractor were matched precisely and monitored every 3 min throughout the rearrangement phase. The tractor's speed was determined by measuring the distance (a measuring wheel calibrated in centimeters was rolled on the ground with the tractor) traveled in 60 s; the treadmill's speed was measured in the same way, so the measuring wheel rolled with the treadmill's tread while participants walked on it.

Results and Discussion

After the biomechanically faster condition, participants tended to walk too far. The first-trial errors averaged 25% ($SD = 17$), and participants walked significantly farther on the first posttest than on the pretests, $t(7) = 4.15, p < .05$. The same pattern was found for the repeated-trials errors, which averaged 15% ($SD = 13$), which was also significantly greater than on the pretests, $t(7) = 3.35, p < .05$.

Seven of the 8 participants also overshot in the matched speed condition as well. The first-trial errors averaged 7% ($SD = 10$), and participants walked significantly farther on the first posttest than on the pretests by one-tailed test, $t(7) = 2.35, p < .05$. The participants tended to overshoot across the set of repeated trials as well; the repeated-trials errors averaged 5% ($SD = 6$), and the posttests were significantly different from the pretests, $t(7) = 2.35, p < .05$. These results indicate that walking was recalibrated because of the eye-height discrepancy.

Finally, the participants erred by overshooting significantly farther in the biomechanically faster condition than in the matched speed condition for the first-trial posttests, $t(7) = 2.37, p < .05$; repeated-trials errors showed the same pattern, which although not significant, was in the same direction; $t(7) = 1.85$. Thus, the asymmetrical pattern does not seem to reflect either the differences in treadmill and towing speeds used across the two conditions, nor the fact that the undershoot errors must inevitably be negatively skewed relative to the overshoot errors. Instead, the results indicate the recalibration may be due to the discrepant eye heights added to the recalibration due to the discrepant rates, accounting for the asymmetrical pattern of errors across the biomechanically faster and biomechanically slower conditions in Experiment 1.

Experiment 5: Do the Changes in Distance Walked Result From Change in Stride Length, Cadence, or Number of Paces?

The results show that after the biomechanically faster condition, participants walked farther on their posttests than on their pretests, whereas after the biomechanically slower condition, participants walked shorter distances on their posttests. The participants might have varied the distances walked by changing a number of different features of their gait. For example, they may have kept a constant cadence and stride length and walked a larger or smaller number of paces (or for a longer or shorter amount of time). Alternatively, they may have increased or decreased their cadence, producing a larger or smaller number of paces during the same amount of time. And finally, they may have lengthened and shortened their stride length, walking the same number of paces at the same cadence and for the same amount of time. Experiment 5 was designed to investigate this issue directly, by recording cadence, number of paces, and stride length during the pretests and posttests.

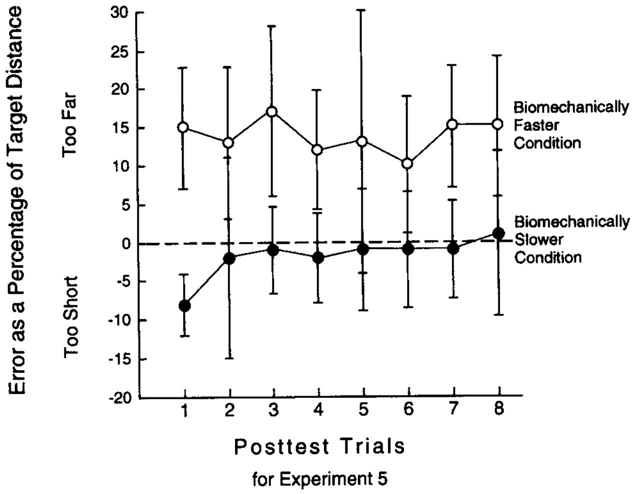

Figure 3. The average errors as a percentage of target distance from Experiment 5 for the biomechanically faster (top panel) and biomechanically slower (bottom panel) conditions. The bars indicate the size of one standard deviation.

Method

Eight adults participated in both conditions of the experiment. There were nine pretest trials and nine posttest trials, modeled closely after the tests used in the earlier experiments. In the earlier experiments a constant 8-m target distance was always used. In the present experiment, target distance was varied, so that equal numbers of 8-, 9-, and 10-m distances were randomly interspersed across the repeated trials. Half of the participants took part first in the biomechanically faster condition, where the walking rate was 8 kph and the environmental-flow rate was 4 kph; the other half participated first in the biomechanically slower condition, where the walking rate was 5 kph and the environmental-flow rate was 10 kph. A tractor was used to tow the treadmill and trailer during the rearrangement phases, and the exact speeds were measured as in the previous experiment. The walking distances were measured in the same way as in the earlier experiments. In addition, the tester used a stopwatch to record the amount of time the participant walked during each trial and counted the number of steps taken during each trial.

Results and Discussion

Replicating Experiment 1, the participants walked too far after the biomechanically faster condition and not far enough after the biomechanically slower condition (see Figure 3). In the biomechanically faster condition, the first-trial errors averaged 15% (*SD* = 8), significantly longer than in the pretests, $t(7) = 5.35$, $p < .05$; similarly, the repeated-trials errors averaged 14% (*SD* = 8), significantly longer than in the pretests, $t(7) = 4.70$, $p < .05$. In the biomechanically slower condition, the first-trial errors averaged -8% (*SD* = 4), significantly shorter than in the pretests, $t(7) = 5.49$, $p < .05$. The repeated-trials errors averaged -3% (*SD* = 6); although they showed the same pattern, the difference was not statistically significant, $t(7) = 1.40$.

Analysis of the gaits showed that participants significantly increased (after the biomechanically faster condition) or decreased (after the biomechanically slower condition) their numbers of steps walked from the pretests to the posttests, whereas there were no significant changes in their step length, walking speed, or cadence. For the biomechanically faster condition, participants averaged 9 (*SD* = 1) steps on the first pretest trial versus an average of 11 (*SD* = 1) on the first posttest trial, $t(7) = 3.97$, $p < .05$. The other features of gait changed little for the same pretests and posttests and some of the changes approached statistical significance; the stride lengths changed from an average of 0.83 m (*SD* = .08) to 0.86 m (*SD* = .13); the speeds changed from 1.32 mps (*SD* = .23) to 1.42 mps (*SD* = .37); and the cadences changed from 1.3 steps/s (*SD* = 5) to 1.5 steps/s (*SD* = .60). The gaits averaged across the repeated trials showed the same pattern. For the biomechanically slower condition, participants averaged 10 steps (*SD* = 1) on the first pretest trial versus an average of 8 (*SD* = 2) on the first posttest trial, $t(7) = 2.59$, $p < .05$. The other features of gait changed little and nonsignificantly for the same pretests and posttests; the stride lengths changed from an average of .82 (*SD* = .08) to .94 (*SD* = .22); the speeds averaged 1.30 mps both for the pretest (*SD* = .35) and posttests (*SD* = .23); and the cadences were 1.3 steps/s (the *SD*s were .4 and .5).

The gait data provide a chance to check whether the calibration of locomotion is organized at a relatively specific anatomical level, so that walking is calibrated independently for each rate. During the rearrangement phase, the treadmill forced participants to walk at a particular rate, but during the tests each participant picked his or her own pace. Because of this, some participants were tested while walking at rates that were close to the treadmill's rate, whereas others were tested at rates that were quite different. We wished to assess whether similarity in posttest walking speed to the treadmill speed (calculated as the absolute difference between each participant's average speed during the posttest trials and the 6 mph treadmill speed) was predictive of the amount of change in calibration (calculated for each participant as the difference between the first posttest and the averaged pretest). The resulting correlations were small and nonsignificant, $r(7) = -.089$ for the biomechanically faster condition and $r(7) = -.217$ for the biomechanically slower condition.

Overview of Experiments 6–10: Tests of Generalization to Functionally Related and Unrelated Actions

The first set of experiments demonstrated changes in the calibration of forward walking. The second set was designed to probe how the calibrations are organized by testing for generalization from the action practiced during the rearrangement phase to either a functionally related or unrelated action performed during the test phases. Experiments 6 and 7 tested for generalization, respectively, of a change in calibration of forward walking to throwing and vice versa. Experiment 8 tested for generalization of change in the calibration of forward locomotion to side-stepping; the gaits of forward walking and side-stepping differ, whereas they both serve the function of translating the walker's perspective. Experiments 9 and 10 tested for generalization, respectively, of a change in the calibration of forward walking to turning in place and vice versa. The gaits of forward walking and turning in place differ, and in addition they serve the different respective functions of changing the walker's observation point (involving a translation in perspective) and changing the walker's heading (involving a rotation in perspective).

Experiment 6: Does the Change in Calibration of Forward Walking Generalize to Throwing?

Experiments 1–5 demonstrated change in the calibration of forward walking, but they did not provide information about how the calibrations are organized. Experiment 6 was designed to evaluate whether change in the calibration of forward walking generalizes to throwing. This was tested by asking participants to view a target, close their eyes, and on half the trials to try to throw a bean bag so it would land on the target location and on the other trials to try to walk to the target location without vision.

The expected change in the calibration of forward walking should generalize to throwing if the actions are globally calibrated relative to visually perceived distances. For example, during the rearrangement phase in the biomechanically faster condition, participants learned to expend more effort than before to walk a given distance. A global organization would be demonstrated if the actions or the visual perceptions were scaled in terms of the global amount of effort. If actions are globally scaled in terms of effort, then during the rearrangement phase in the biomechanically faster condition participants would have learned to increase their forward-walking effort by a given factor, and they would increase their throwing effort by the same factor and throw too far during the generalization tests. If visual perception of distance is globally scaled in terms of the effort involved in needed actions, then the rearrangement phase in the biomechanically faster condition would have induced participants to visually perceive the target distances as longer than before. Then during the generalization tests, they would "misperceive" the target distances and throw too far as well.

Method

The participants were 8 university students. The methods were closely modeled after the earlier experiments. During the rearrangement phase, all participants were in the biomechanically faster condition. As in Experiment 5, the tractor towed the treadmill at 5 kph and the treadmill moved at 10 kph. This experiment differed from the earlier ones because tests of throwing were alternated with tests of forward walking. In addition to practicing walking without vision on their own during the warm-up phase, participants were given bean bags and asked to practice throwing them at targets for about 2 min as well.

Altogether there were 12 pretest and 12 posttest trials. Half were forward-walking trials, which were alternated with throwing trials; half of the participants started with a forward-walking trial and the others with a throwing trial. The 8-, 9-, and 10-m target distances were used, and a third of the throwing and a third of the forward-walking trials were conducted at each distance.

The forward-walking tests were exactly the same as those in Experiment 5. For the throwing tests, bean bags were made by filling children's athletic socks with about 100 g of birdseed and tying the ends so that they were egg-shaped. Participants were asked to use an underhanded throw in an attempt to have the bean bag land exactly on the target. Sometimes the bean bag bounced a bit, so the tester watched where it first landed and recorded its distance with the measuring tape. For the throwing tests, a tester stood at the target location; the blindfold and sound system were used, exactly as in the forward-walking tests.

Results and Discussion

The findings were that walking, but not throwing, changed in calibration while participants walked on the treadmill. For the forward-walking tests, all 8 participants overshot on the first trial; the first-trial errors averaged 17% ($SD = 7$), significantly farther than in the pretests, $t(7) = 6.80$, $p < .05$. Similarly, all 8 subjects overshot across all trials, and the repeated-trials errors were 13% ($SD = 4$), again significantly farther than in the pretests, $t(7) = 8.80$, $p < .05$. For the throwing tests, only 3 of the 8 participants threw too far on the first trial; the first-trial errors averaged −1% ($SD = 6$), slightly shorter than in the pretests, from which they did not differ significantly. Similarly, only 3 participants threw too far over all trials, and the repeated-trials errors averaged only −1% ($SD = 5$).

The results show that the change in forward walking did not generalize to throwing. They are inconsistent with the hypothesis that the calibrations are globally organized. If the rearrangement phase had induced a global change in scale of effort or a change in visual perception, then the participants should have thrown too far during the posttests. But this conclusion depends on the null finding that the throwing distances did not change from the pretests to the posttests. However, it might have been the case that throwing did change but the present test methods were not sensitive enough to detect it. Experiment 7 was designed to test this possibility.

Experiment 7: Does Change in Calibration of Throwing Generalize to Forward Walking?

Whether throwing footballs or frisbees, skilled athletes tune the calibration of their throws to fit the shifting winds. The purpose of Experiment 7 was to determine whether the present methods are sensitive enough to detect changes in the calibration of throwing induced not by wind, but by launching the throws from a moving trailer. If the methods detect change in the calibration of throwing, will the change in calibration generalize to walking?

Method

The participants were 6 college students. Altogether there were 18 pretest and 18 posttest trials like those in Experiment 6; half assessed the forward-walking and half throwing. Equal numbers of the walking and the throwing trials were directed at 8-, 9-, and 10-m targets.

Unlike the earlier experiments, the two conditions of the rearrangement phase were designed to induce a recalibration of throwing, not of forward walking. As before, participants stood atop the treadmill while it was towed on a trailer behind a minivan. Participants were asked to pick spots on the ground to serve as targets and to try to hit them with bean bags while they were being towed, watching for feedback after each throw.

In the throw-harder condition, participants faced backward while being towed away from their targets; they were asked to throw at targets that were directly in front of them. In the throw-easier condition, participants faced forward; because the vehicle was directly in front of them, participants were asked to throw at targets that were about 20° off to the side. The vehicle's average speed was 8 kph, ranging from 5 to 12 kph. Participants threw a total of 34 times, so the rearrangement phase lasted 3 to 5 min, depending on how rapidly participants elected to throw.

Results and Discussion

The findings were that throwing, but not walking, changed in calibration while participants threw from the trailer. This was especially clear for the throw-harder condition, in which all 6 participants overshot the target on the first trial; the first-trial errors averaged 19% (*SD* = 12.8), showing that participants threw significantly farther in the posttest trials than in the pretest trials, $t(5) = 5.62, p < .05$. Similarly, all 6 participants threw too far across the repeated trials. The repeated-trials errors averaged 15% (*SD* = 6.6); the posttest throws were significantly farther than those in the pretests, $t(5) = 5.42, p < .05$. On the other hand, the participants did not tend to walk too far. Two participants walked farther on the first posttest trial than in the pretest trials, 1 showed no change, and 3 walked shorter distances. The first-trial errors averaged −3% (*SD* = 4.0), and the results from the posttests did not significantly differ from those from the pretests. Similarly, the repeated-trials errors averaged 2% (*SD* = 3.1), and the posttest results did not significantly differ from the pretest results.

Although in the predicted direction, the undershoot was not statistically significant in the throw-softer condition, because 1 of the participants did not conform to the predicted direction, although 5 of the 6 participants did conform. The first-trial errors averaged −3% (*SD* = 4.1); the posttests did not significantly differ from the pretests, although they were in the predicted direction, $t(5) = 1.98$. For the repeated-trial errors, only 4 of the 6 participants undershot; they averaged −1% (*SD* = 8.8), and the averaged posttest results did not significantly differ from the pretest results. Participants showed no tendency to undershoot on their walking trials. The first-trial errors averaged −2% (*SD* = 4.8), and the results from posttest trials did not significantly differ from the pretest-trial results. Similarly, the repeated-trials errors averaged 2% (*SD* = 4.6), and the posttest-trial results did not significantly differ from the pretest-trial results.

The overshoot was larger after the throw-harder condition than was the undershoot after the throw-softer condition, although they did not significantly differ in magnitude. We do not know the reason for this difference in the two throw conditions, but two points may be relevant. First, the throw-harder condition may have been more optimal than the throw-softer condition, because participants had a clear throwing path in the former, whereas in the latter they needed to throw to the side of the vehicle. Second, eye-height scaling logically might account for the asymmetrical effect in throwing for the same reasons as it did for forward walking.

Experiment 8: Does the Change in Calibration of Forward Walking Generalize to Side-Stepping or Is It Gait Specific?

Human gaits, like forward walking, side-stepping, skipping, and running all use the legs to accomplish the same general function, namely, changing observation point without changing facing direction. But they differ sharply in pattern because they involve different muscles and different patterns of contraction. Experiment 8 was designed to assess whether the change in calibration of forward walking generalizes to side-stepping. Biomechanically, a complete cycle of forward walking consists of a gradient of heel-to-toe pressure on one foot while the other foot swings forward, heel-to-toe pressure on the other foot while the first foot swings forward, and so on, without pause. The side-stepping gait used here consists of swinging one foot to the side, planting the foot, moving the other foot beside it, planting that foot, and stepping out again to the side with the original foot. Unlike forward walking, side-stepping consists of a side-to-side gradient of pressure on one foot, a side-to-side gradient on the other foot, and a full stop between step cycles. Because of the full stop, the speed of side-stepping averaged only 60% of the speed of forward walking.

To evaluate whether the change in calibration of forward walking generalizes to side-stepping gait, participants walked forward on the treadmill in the biomechanically faster condition during the rearrangement phase. For half of the pretest and posttest trials, they were asked to walk to the remembered target location by forward walking, and for the other trials, they were asked to walk by side-stepping.

Method

The participants were 8 undergraduate students. The biomechanically faster condition of the rearrangement phase was modeled after the earlier experiments, so participants walked 10 kph on the treadmill while being towed 5 kph behind the tractor. The original tractor was unavailable for rental, so a different tractor was used. The new tractor had a larger cross-sectional profile (so it occluded a region measuring about 30° × 20° of visual field, whereas the former tractor occluded about 25° × 18°). In addition, it had a black roll bar that framed an additional region of the field that was 20° × 15°.

Results and Discussion

The main finding is that the participants walked too far during both the forward walking and the side-stepping posttests, which did not significantly differ from each other. For the forward walking, 7 of the 8 participants walked too far on the first-trial posttest, which averaged 6% (*SD* = 6), $t(7) = 2.59$, $p < .05$. The same pattern was found for the repeated-trials errors, which averaged 9% (*SD* = 5); the distances in the posttests were significantly farther than in the pretests, $t(7) = 2.65$, $p < .05$. For the side-stepping, all 8 of the participants walked too far on the first-trial posttest, which averaged 9% (*SD* = 4.7); the distances walked in the posttests were significantly farther than in the pretests, $t(7) = 4.41$, $p < .05$. The same pattern was found for the repeated-trials errors, which averaged 9% (*SD* = 5); the distances walked in the posttests were significantly farther than in the pretests, $t(7) = 5.30$, $p < .05$. This indicates that the change in calibration is not tied to a specific gait or rate, because it generalized from forward walking to side-stepping.

Experiment 9: Does the Change in Calibration of Forward Walking Generalize to Turning-in-Place?

The results of Experiment 8 indicate that perceptual-motor coordination is not organized around narrow, anatomically defined features of action. This finding is consistent with the hypothesis of a functional organization, but alternatively, may indicate that leg activity per se, not its particular function, globally changes in calibration. If this is the case, then change in the calibration of forward walking should generalize even to walking gaits that do not serve to change observation point and are not accompanied by translation of perspective. To evaluate this, we tested turning in place, a walking gait that serves to change heading, not observation point, and is accompanied by a rotation of perspective, not a translation.

Participants walked on the treadmill in the biomechanically faster condition as during the rearrangement phase of Experiment 9. Half of the pretests and the posttest consisted of forward walking trials. The others were turn-in-place trials, during which participants were asked to view a target, close their eyes, and turn a full circle in order to face it again.

Method

The participants were 8 undergraduate and graduate students. The rearrangement phase was the same as the biomechanically faster condition in Experiment 8, in which participants walked on the treadmill at 10 kph while being towed behind a tractor at 5 kph; the tractor did not have a rollbar. There were a total of 12 pretest and 12 posttest trials. Half were forward-walking trials, like the earlier experiments. The others were turn-in-place trials during which participants were asked to look straight ahead at the target and then occlude their vision and attempt to turn a full circle in order to face it again; half of the participants turned clockwise and half counterclockwise. The forward-walking trials were alternated with the turn-in-place trials; half of the participants started with the forward-walking trials and the others with the turn-in-place trials. The accuracy of forward walking was measured as in the earlier experiments. The accuracy of turning was assessed with a compass. Participants held a compass graduated in 2° units while turning. Errors were calculated by subtracting the compass reading at the end of each trial from the correct compass reading, as determined by line of sight with the same compass.

Results and Discussion

The results were that participants consistently walked too far during the forward-walking tests but not during the turn-in-place tests. For the first posttest of forward walking, all 8 participants walked farther during the posttests than during the pretests; the first-trial errors averaged 18% (*SD* = 11), the distances walked in posttests were significantly farther than in the pretests, $t(7) = 4.38$, $p < .05$. The same pattern was found for the repeated-trials errors, which averaged 12% (*SD* = 10); the posttests were significantly farther than the pretests, $t(7) = 3.50$, $p < .05$. On the other hand, for the first-trial turn-in-place tests, only 4 of the 8 participants turned too far; first-trial errors averaged 2% (*SD* = 11) of the target distance (this was a full turn), and the results from the posttests did not significantly differ from those of the pretests. The same pattern was true for the repeated-trial errors, which averaged 0.6% (*SD* = 2.4).

The change in calibration of forward walking did not generalize to turning-in-place walking. The changes in calibration observed in the present experiment were larger than those observed in Experiment 8, similar in magnitude to those observed in the first seven experiments. There was only one important methodological difference that distinguished Experiment 8 from Experiment 9 and the earlier experiments—a rollbar framed the visual field in Experiment 8 and did not frame it in the other experiments. We believe that the smaller changes in calibration observed in Experiment 8 resulted from the rollbar's effect of framing the visual field during the rearrangement phase.

Experiment 10: Does the Change in Calibration of Turning-in-Place Generalize to Forward Walking?

The results of Experiment 9 indicate that leg activity did not globally change in calibration. Instead, the change in calibration might be functionally specific, limited to walking that serves to change one's observation point. But this conclusion depends on accepting the null finding that the change in forward walking did not generalize to turning in place. Perhaps the test methods were simply not sensitive enough to detect change in the calibration of turning in place. Experiment 10 was designed to evaluate this. The rearrangement phase was modeled after the biomechanically faster condition used in the earlier experiments, but it was designed to induce change in the calibration of turning in place, not in forward walking. The pretests and posttests consisted of both forward walking and turning in place, to test for change in the calibration of turning movements and, if observed, assess whether it generalizes to forward walking.

Method

The participants were 6 undergraduate students. There were 12 pretest and 12 posttest trials, which were conducted exactly as the tests in Experiment 9; for example, half were forward-walking trials (to 8-, 9-, and 10-m targets), which were alternated with turn-in-place trials. Half of the participants started with a forward-walking trial, and the others started with a turn-in-place trial.

A large turntable was used to rearrange the rates of biomechanical activity and environmental flow. The turntable consisted of a disc 122-cm in diameter, which was mounted atop a metal base 35 cm high containing motors. A T bar through the center of the disc was individually adjusted to waist height (see Figure 4). One electric motor was linked by a chain drive to the T bar; the T bar could be driven at variable speeds and in either direction. A second electric motor was linked by a friction drive to the turntable, which also could be driven at variable speeds and in either direction. A biomechanically faster condition was arranged in which participants walked by turning in place biomechanically at 10 rpm while they were physically rotated relative to their surroundings at 5 rpm.

During the rearrangement phase, participants were asked to grasp the T bar and step in order to keep the T bar parallel to their hips. Then the T bar was turned on at 5 rpm, and finally the turntable was turned on in the opposite direction at 5 rpm. The result of this was that the participants' legs were moving biomechanically at a rate that normally would result in 10 rpm of whole-body movement. But in this contrived situation, their heads and bodies actually turned only at 5 rpm. The walking gait was a rotary side-stepping that was centered around the stem of the T bar. Half of the participants turned clockwise, and the others counterclockwise. For each participant, direction of the turn-in-place tests was the same as the walking direction during the rearrangement phase on the turntable.

Results and Discussion

When attempting to walk a full turn in order to face the target, participants consistently erred by turning too far on the turning posttests, whereas they did not tend to walk too far on the forward-walking posttests. For the first-trial turn-in-place tests, all 6 participants turned too far, averaging 10% (*SD* = 3) more than the full turn needed to face the target; errors from rotations on posttests were significantly longer than on the pretests, $t(7) = 7.39, p < .05$. The same pattern was true for the repeated-trials errors, which averaged 8% (*SD* = 3); rotations on posttests were significantly longer than on pretests, $t(7) = 6.14, p < .05$. For the forward-walking tests, neither the first-trial errors, which averaged 1% (*SD* = 7), nor the repeated-trials errors, which averaged 3% (*SD* = 5), showed significantly different pretest versus posttest errors.

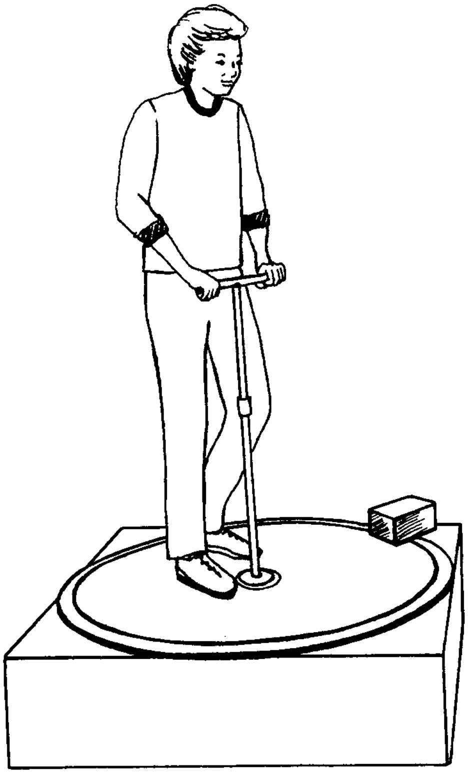

Figure 4. Drawing of the turntable used to induce change in the calibration of turning-in-place in Experiment 10. The disc underfoot is controlled by one variable speed motor, and the T bar is controlled by another variable speed motor.

As in the posttests after change in calibration of forward walking, participants were unaware of turning too far, and instead all six guessed that, if they had erred at all, they had turned too little and had stopped short of the target. Participants reported that their perceived rate of turn seemed slower, relative to the remembered surroundings, than their actual rate. Although they turned too far during the rotation tests, they did not walk too far during the forward-walking tests, and so the change in calibration of turning did not generalize to forward walking.

General Discussion

The 10 experiments demonstrate experimentally induced changes in the calibration of walking, throwing, and turning

Table 1
Summary of the Ten Experiments

	Rearrangement phase			Test phase			
						Observed error[a]	
Experiment	Activity	Biomechanical rate (kph)	Environmental rate (kph)	Activity	Predicted error (%)	*M* (%)	*SD*
1. Demonstration of changes in the calibration of locomotion	Forward walking	8	5	Forward walking	60	18	8*
		7	17		−59	−7	2*
2. Is the asymmetrical change in calibration due to an additional effect of biomechanical activity alone?	Forward walking			Forward walking			
	Eyes open	4	0	Eyes open	Overshoot[b]	10	3*
	Eyes closed	4	0	Eyes closed	0	3	3
3. Is the asymmetrical change in calibration due to an additional effect of environmental flow?	Forward walking	0	5	Forward walking	0	−3	4
4. Is the asymmetrical change in calibration due to the discrepant eye heights from the rearrangement phase to the posttest phase?	Forward walking	8	4	Forward walking	100	25	17*
	Forward walking	8	8	Forward walking	100	7	10*
5. Do the changes in distance walked result from change in stride length, cadence, or number of paces?	Forward walking	8	4	Forward walking	100	15	8*
	Forward walking	5	10	Forward walking	−50	−8	4*
6. Does the change in calibration of forward walking generalize to throwing?	Forward walking	10	5	Forward walking	100	17	7*
	Forward walking	10	5	Throwing	100	1	6
7. Does the change in calibration of throwing generalize to forward walking?	Throwing	0	8	Throwing	Overthrow[b]	19	13*
				Forward walking		−3	4
	Throwing	0	−8	Throwing	Overthrow[b]	−3	4
				Forward walking		−2	5
8. Does the change in calibration of forward walking generalize to side-stepping, or is it gait specific?	Forward walking	10	5	Forward walking	100	6	6*
	Forward walking	10	5	Side-stepping	100	9	5*
9. Does the change in calibration of forward walking generalize to turning-in-place?	Forward walking	10	5	Forward walking	100	18	11*
	Forward walking	10	5	Turning-in-place	100	2	11
10. Does the change in calibration of turning-in-place generalize to forward walking?	Turning-in-place	10[c]	5[c]	Turning-in-place	100	10	3*
				Forward walking		1	7

[a] First-trial errors only. [b] No predicted magnitude of error. [c] rpm.
*$p < .05$.

in place (see Table 1). During the posttests, participants perceived their actions as accurately matching the remembered target distances. They were not aware of the direction of the posttest errors, guessing incorrectly on 70% of the sets of blocked trials inducing change in calibration. When the change in calibration resulted in errors involving too much distance, the participants reported they may have erred by walking, throwing, or turning too short a distance. *Functionally, their* rates of walking, turning, and throwing were calibrated in terms of their remembered surroundings; participating in the rearrangement phases of the experiments induced change in the calibration. The same pattern was found when participants erred by walking too short a distance.

The change in calibration was most systematically demonstrated for forward walking across Experiments 1, 2, 4, 5, 8, and 9. A total of 50 participants experienced the rearrangement in the biomechanically faster condition, and 49 of them walked too far during the first posttest trial. A total of 12 participants experienced the rearrangement in the biomechanically slower condition, and all 12 walked too short during the first posttest. Experiments 2 and 3 demonstrated that the change in calibration was not due to simple aftereffects of biomechanical activity (Experiment 2) or environmental flow (Experiment 3). Experiments 1 and 5 indicated an asymmetry in the magnitude of the changes, with the biomechanically faster condition yielding greater effects than the biomechanically slower condition. Experiments 2, 3, and 4 taken together suggest that this asymmetry is due to an additional factor causing the change in calibration, namely, the discrepancy between the eye height in the rearrangement phase and the posttest phase of the experiments. The results of Experiment 5 indicated that participants did not change their step lengths, walking speeds, or walking cadences significantly from the pretests to the posttests. Instead, the changes in the distances walked resulted from corresponding changes in the number of steps (or amount of time) taken to cover a given distance to a target.

Experiments 6 through 10 were focused on how the changes in calibration generalized to different actions. Experiment 6 demonstrated that the change in calibration of forward walking was specific and did not generalize to throwing. Experiment 7 showed that the calibration of throwing itself can be changed given rearrangement conditions analogous to those used for forward walking; in addition, it showed that the change in calibration of throwing did not generalize to forward walking. Experiment 9 demonstrated that the change in calibration of forward walking did not generalize to turning in place. And Experiment 10 showed that the calibration of turning in place itself can be changed given appropriate rearrangement conditions; in addition, it showed that the change in calibration of turning in place did not generalize to forward walking.

Thus, the changes in calibration did not generalize across the different functional categories of action that were evaluated, but they did generalize across the variations in speed (as seen in the analysis of the gait data in Experiment 5) and gait (Experiment 8) that all served to translate one's perspective. The empirical findings fit the "functional" model of perceptual-motor coordination. They are incompatible with both the "action-specific" and the "global" models.

The experiments were designed to demonstrate methods of inducing change in the calibration of three actions and then to apply the methods to probe the organization of the calibration for human locomotion. The remaining discussion is focused on three issues. The first issue concerns the magnitude of the observed errors, which reflects the amount of change in calibration induced by our procedures. The second issue concerns the integration of actions and remembered surroundings across space and time. Finally, the third issue concerns alternative "intermediate" models of perceptual-motor organization.

Magnitudes of the Observed Changes in Calibration

Evidence of a change in calibration consisted of change in the posttest errors relative to the pretest errors. These changes occurred consistently in the predicted direction in the case of every experiment and almost every participant. But the changes in error were considerably smaller than would have been observed if the participant's posttest responses had been exactly tuned to the conditions experienced during the rearrangement phases. The expected percentages of error appear in Table 1 together with the observed first-trial errors averaged across participants. Even for the best example (Experiment 1), the average magnitude of the observed first-trial errors was only 27% of the predicted magnitude. The magnitudes of change in calibration are consistent with the incomplete changes observed in studies of adapting to prismatic distortion (Welch, 1978).

Consider two possible causes of the limited changes in calibration. First, the limited changes might reflect that the system is relatively slow to change. For example, if one supposes that the plasticity was engineered to compensate mostly for anatomical growth in limbs, then it makes sense to suppose that the system would be relatively slow to change its calibration, far slower than the 5 to 10 min rearrangement phases used throughout the present experiments. But on the other hand, if the plasticity serves to compensate for short-term fluxuations in one's situation (e.g., fluxuations involving weather, context, and tool use), then it makes sense to suppose that the system would rapidly change its calibration. In this case, the limited changes we obtained may reflect limits in our methods, in which the rearrangement phase occurred while participants were towed behind a vehicle and the test phases occurred while they stood on the ground.

Consider four features of the method that may have limited the magnitudes of the observed effects. First, as suggested by Redding, Clark, and Wallace (1985) in their studies of eye–hand coordination, the participants understood that the rearrangement and posttest situations were different, and perhaps they used this knowledge strategically, reducing the errors by intentionally walking a longer or shorter distance than seemed correct. Second, for safety's sake, some participants looked while stepping down from the treadmill and trailer. Although very brief, such feedback after the rearrangement phase and before the posttests may have influenced their calibration. Third, in natural situations, rates of biomechanical activity and environmental flow are coupled continuously across a wide range of walking speeds, but in our contrived situation we were able to rearrange only a fixed walking speed. And fourth, the towing vehicle was always in the participant's field of view during the rearrangement phase. This would have both reduced the size of the optical flow field and provided a stationary visual frame of reference for comparison, making the environmental flow less salient. The results of Experiment 8, in which the towing tractor had a large tow bar, make this all the more plausible.

Time, Space, and Mental Representation

In the present experiments, participants viewed a target, closed their eyes, and then were asked to coordinate forward walking, turning-in-place, or throwing with the target's remembered location. Even though their eyes were closed, the participants reported an expproprioceptive awareness of the target location throughout the test trials. During the forward-walking and turning-in-place trials, participants reported keeping up to date on their changing position relative to the remembered target; during the throwing tests, they reported continuing awareness of the bean bag's trajectory. We think a fair summary of their reports is that their experience of the surroundings without vision was similar to, although less precise than, their perception with vision.

Their reports reflect an interesting type of dynamic imagery, implying that their motor activity is integrated over space and time with their remembered surroundings (Rieser, Garing, & Young, 1994). For locomotion, this means that the efferent and afferent information associated with forward walking and turning in place was integrated with knowledge of their remembered surroundings in order to update their changing position relative to the target object. For throwing it means that the efferent and afferent information associated with throwing specified the bean bag's trajectory relative to the remembered surroundings.

The reports imply that mental representations of the surroundings preserve the same geometric relations as visual perceptions and that actions are calibrated in the scale of the remembered surroundings. However, the methods used in the present experiments do not provide a means to validate their impressions. The reason for this is that participants could have programmed their actions while looking at the target and then carried out the preprogrammed actions while blindfolded during the tests. To validate their reports, what is needed are studies in which participants do not have the opportunity to preprogram their actions. Several earlier studies of locomotion and of throwing show that people coordinate their walking and throwing with their remembered surroundings, even in situations in which they could not have preprogrammed their actions.

As an example of locomotion, Rieser, Guth, and Hill (1986) showed participants five targets from one observation point in an unfamiliar room, blindfolded them, guided them along a J-shaped path to a novel test location (this resulted in a translation in perspective combined with a rotation), and asked them to aim a pointer at the different remembered targets. In the destination-known condition, participants were shown their test location ahead of time so they had the chance to preprogram their pointing responses from their future test location. But in the destination-unknown condition, they did not have advance knowledge of their future test location. The participants pointed with similar degrees of error in both conditions (averaging 20 and 22 degrees of error, respectively; see also Loarer & Savoyant, 1991). Similar results have been found with young children (Rider & Rieser, 1988; Rieser et al., 1994; Rieser & Rider, 1991) and for persons who are blind (Rieser et al., 1986; Talor, 1993).

As an example of throwing, Thomson (1983) assessed throwing toward remembered targets in a situation where the throw could not have been preprogrammed. Adults viewed a target object, which was located from 3 to 21 m straight ahead of them, then closed their eyes and began walking toward the target's remembered location. Finally, at an unpredictable point during their walk, they were asked to stop and throw a bean bag the rest of the way to the remembered target. Because the throwing point was unpredictable, the distance of the throw could not have been preprogrammed (see also Eby & Loomis, 1987). These earlier studies show that human actions can be coordinated with the changing perspectives of one's remembered surroundings while walking without vision. They indicate that the efferent and afferent information associated with walking and throwing are integrated over space and time with one's remembered surroundings. We suppose this integration reflects the calibration of perception and action.

Models of Visual–Locomotor Organization

The data of the present study can be used to rule out the two extreme models of organization. The "global model" postulates that perceptual-motor coordination is unified so that tuning the calibration of one action to fit a given situation generalizes to all other types of action that are affected by the situation. This does not fit the demonstrations that change in the calibration of forward walking did not generalize to throwing or turning in place. The "anatomically specific" model postulates that perceptual-motor coordination is organized so that tuning the calibration of particular effectors to fit a given situation generalizes only to other instances of actions involving the same effectors. This does not fit the demonstrations that change in the calibration of forward walking did generalize to different rates of forward walking and to side-stepping.

The functional model suggests a system engineered efficiently so that practice fine-tuning one action to fit a situation automatically fine-tunes other actions that serve the same goal. This model fits both the positive and the negative findings presented here. As predicted by the functional model, change in the calibration of forward walking generalized to side-stepping, which also resulted in a translation of perspective. But the calibration of forward walking did not generalize to turning in place or to throwing; in addition, change in the calibration of turning in place and throwing did not generalize to forward walking.

Functional Model Compared With a Limb–Effector Model

How does the functional model compare with other "intermediate" models? A straightforward "intermediate" alternative is a limb–effector model, which postulates that limbs are calibrated, not particular functional actions. Functions are often accomplished in stereotyped ways and with the same limbs, so a limb–effector organization would provide some of the advantages of a functional organization. For example, the legs (not arms or mouth) are often used to change observation point and heading; the arms and hands are often used for hurling objects; and the mouth and articulators are often used for communicating.

But empirically the limb–effector model fits two of the present findings and does not fit two other findings. Forward walking and throwing were effected with different limbs and, as predicted by the limb–effector model, change in the calibration of forward walking did not generalize to throwing, and change in throwing did not generalize to forward walking. But the limb–effector model does not fit two other findings. Forward walking and turning in place were both accomplished with the legs, and contrary to the model's prediction, change in the calibration of forward walking did not generalize to turning in place, and change in turning in place did not generalize to forward walking.

Thus, the evidence here shows that a simple limb–effector model is not correct, whereas it fits the functional model. But the functional model was contrasted with the limb–effector model only for one pair of actions, namely, forward walking and turning in place. It could be that neither simple model will do and that different hybrid models are needed to fit different actions. It is easy to think of additional ways to contrast the two models through systematic studies of locomotion, hurling objects, and communicating. Locomotion is often accomplished by walking on foot, but gymnasts walk on their hands, and persons with some disabilities locomote with wheelchairs. According to the functional model, change in the calibration of forward locomotion on foot should generalize to these other two methods of forward locomotion. Hurling objects is often accomplished by throwing them by hand, but people also kick things by foot, and sometimes they use a blowgun or children's peashooter. According to the functional model, change in the calibration of throwing objects by hand should generalize to kicking and to "peashooting." Finally, communication is often accomplished verbally, but people also use their hands when applauding or when using American Sign Language. According to the functional model, change in the calibration of verbal communication should generalize to instances of manual communication (Bellugi, Poizner, & Klima, 1989).

Theory and Method to Determine Functional Organization

Theoretically, we take organization of coordination to refer to the way different perceptual-motor actions cluster together, and we have probed the clustering empirically, investigating the generalization of changes in the calibration of one action to other actions. Our theoretical approach is rooted in a functionalist bias to suppose that perception and action are adapted to fit the actor's goals. The resulting functional model of organization provides a guide for research, indicating sets of actions across which changes in calibration are more and less likely to generalize.

A functional model could be defined purely in terms of the actor's goals, but because psychological goals vary in complexity and time-scale, the resulting model of perceptual-motor organization might be too complex to be useful. For example, consider the collection of goals held by participants in our experiments: to earn spare cash, to follow instructions, to complete the set of pretests, to complete one test trial, to complete one step, and so forth. It is difficult to see how goals that vary so greatly in scope could guide research on coordination, and the functional model proposed here is defined jointly in terms of the actor's goals for an action and the action's immediate, perceptual consequences.

Perceptual-motor learning, where actors notice the covariation between their actions and their perceptible consequences, is the central process accounting for changes in calibration to fine-tune actions to fit changing circumstances. And we have used this process to further limit the model, defining *functionally related* jointly in terms of an action's intended goal and perceptible consequences. So in the present experiments, *forward walking* was defined jointly by the goal of changing observation point accompanied by a perceptible translation in perspective, *turning in place* was defined by the goal of changing heading, and *throwing* was defined jointly by the goal of hurling an object accompanied by a perceptible trajectory.

Conclusions

Perceiving and acting are coordinated so that the force, direction, and timing of actions fit with the actor's goals and take into account the changing circumstances of the action's context. The perceptual and motor systems are mutually calibrated; but theoretically, calibrations cannot map actions onto target locations in a one-to-one correspondence because the needed actions depend on temporary variations in the immediate context as well as on more lasting developmental changes in the actor. The present experiments show that people tune their calibrations after brief periods of action under changed circumstances.

What is the nature of the learning involved in the change in calibration? For forward walking, the experiments show that the change in calibration was mainly due to participants' sensitivity to the changed covariation of biomechanical activity and environmental flow during the rearrangement phase. We theorize that the participants detected this covariation and then later acted on it during the posttest trials.

Characterizations featuring reinforcement-based stimulus–response learning do not fit, because there is no apparent role for reinforcement during the rearrangement phase. Characterizations featuring associative forms of stimulus–response learning have a somewhat better fit, because it is reasonable to suppose that the stimuli were the target objects, and the responses were walking, turning, or throwing. But the characterization seems inadequate when one considers how the stimuli and the responses during the rearrangement phase (when the learning occurred) differed from those during the test phase. The stimuli during the rearrangement phases were dynamic, consisting of optical and nonoptical sources of environmental flow, whereas during the test phase they consisted of a static view of the target. The responses during the rearrangement phases were typically forward walking, but the generalization experiments showed that the learning accomplished with forward walking responses generalized to the very different responses involved in side-stepping.

The learning is congruent with perceptual-motor learning of the type described by E. J. Gibson (1969) in her account of adaptation to visual–motor rearrangement: "The related stimulus events which monitor an action, such as walking toward something, include visual and haptic components, with moment-to-moment feedback adding to the complex.... Compensation for a transformed array requires discovery of new invariants" (p. 213). Within a perceptual learning account, the invariant discovered during the rearrangement phases of the present experiments is the covariation of the flow of biomechanical activity and of the environment relative to the observer.

We suppose, but do not know, that the perceptual-motor learning requires environmental flow information. But perhaps static environmental feedback would suffice. At an extreme, this would be the case if participants walked on the treadmill in the recalibration phase, spotted a target, and were provided only with terminal feedback about when or where they reached the target.

Although the present experiments show that participants calibrate their actions on the basis of such covariation, they do not completely specify the variables entering into it. Much work remains to specify the environmental information that can serve this purpose. For example, we hypothesize that optical flow is one important variable, but what features of the optical flow are most relevant? In addition, are other sources of environmental flow (e.g., flow generated by wind and by sounds) important as well? Can they substitute for optical flow when it is unavailable? Additionally, much work remains to specify the biomechanical information. For example, is efference important? If so, is it effort-related? Is reafference important, and if so, is it modality-specific?

We do not know very much about which features of the actions changed, accounting for the change in calibration. For example, for throwing, we do not know whether the participants adjusted the forces of their throws to adjust for the rearrangement, the angles, or both. Similarly, for turning, we do not know whether the participants adjusted their numbers of steps, the step sizes, or both. We know the most about forward walking, because the results of Experiment 5 showed that the participants increased or decreased the number of steps after the rearrangement phase, not their step lengths or speeds.

But even for bipedal forward locomotion, we suspect that multiple features can be adjusted, depending on the action and situation. For example, although controlling the number of steps proved to be participants' natural method of controlling their forward locomotion while walking, we doubt that number of steps would prove to be the control variable for people equipped with roller skates during the test and rearrangement phases. Whereas varying the number of steps may be the most natural way to control distance walked, varying the horizontal thrust and duration of glide seem to us like similarly natural ways to control distance skated.

How general is the perceptual-motor learning that induces change in the calibration of action to fit with changing circumstances? Consider three of the limits of the completed studies: Only three actions were studied, they were studied in response to temporary changes in the situation, and they were studied with human subjects. Are there reasons to suppose that the learning processes accounting for the calibration and a functional organization also apply to other actions, to child development, and to nonhuman species? Consider each of these three briefly in turn. First, do the learning processes and functional model apply to the calibration of other actions? Although all three actions investigated here resulted in visible trajectories of a moving object (either the self or a bean bag), actions that do not involve visible trajectories also change their calibration from situation to situation. For example, speakers adjust the volume of their public speaking, tuning it jointly to the distance to their listener and to the ambient noise in the situation (Pick, Siegel, Fox, Garber, & Kearney, 1989).

Second, do the processes and model apply to changes in calibration induced by developmental changes as well as situational changes? Children's limbs grow in length, and it is clear that the calibration of perception and action need to take growth into account. But do the resulting changes follow a functional organization? Or alternatively, do they follow, for example, a limb-specific organization, because the changes in calibration are induced by changes in limbs, not situations? And third, do the processes and model apply to nonhuman species? Like humans, nonhuman species are sensitive to changes in the covariation of their biomechanical activity and environmental flow (e.g., for insects, see Hausen, 1993). But are there species differences in how the calibrations are organized, with some engineered to provide more flexible adaptive behavior than others? Whatever future research shows about the generality of the present findings to different actions, ages, and species, the experiments demonstrate that human adults rapidly adjust the calibration of their walking, turning, and throwing to changing circumstances. The patterns of generalization indicate a functional model of perceptual-motor organization.

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