CURRENT DIRECTIONS IN PSYCHOLOGICAL SCIENCE

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When Walking Makes Perception Better

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ABSTRACT—*When we move, the visual world moves toward us. That is, self-motion normally produces visual signals (flow) that tell us about our own motion. But these signals are distorted by our motion: Visual flow actually appears slower while we are moving than it does when we are stationary and our surroundings move past us. Although for many years these kinds of distortions have been interpreted as a suppression of flow to promote the perception of a stable world, current research has shown that these shifts in perceived visual speed may have an important function in measuring our own self-motion. Specifically, by slowing down the apparent rate of visual flow during self-motion, our visual system is able to perceive differences between actual and expected flow more precisely. This is useful in the control of action.*

KEYWORDS—*perception; action; perceptual learning; optic flow; locomotion*

In 1875, Ernst Mach observed that purely visual information could induce a strong sense of self-motion—like an experience of moving when sitting in a stopped train as the adjacent train starts to move. Mach proposed the existence of a spatial sense, distinct from vision, which could nonetheless be activated by visual information. The interaction between visual information and the inner sense of self-motion has received study for over a century, but new insights are now emerging about common situations, like walking, in which multiple sources of perceptual information become interconnected by experience.

Mach's spatial sense is usually associated with a system that uses mechanical sensors in the brain to detect changes in one's state of motion. This *vestibular* system (best known as the system that can make you dizzy when you spin) is also able to measure something about self-motion in a straight line. Because the system is stimulated each time we start to walk or move, its activity is one source of information about our self-motion. There is debate about how well people can judge self-motion when only given vestibular information (e.g., when they are driven blindfolded on a cart). However, it is clear that they can use this information to sense their motion to some extent, especially their changes in motion (Israël, Grasso, Georges-François, Tsuzuki, & Berthoz, 1997).

Nonetheless, the perception of self-motion from visual simulation can also be quite compelling. J.J. Gibson is generally credited with redefining how researchers conceived of the perception of one's body moving in space. Gibson (1966) identified purely visual consequences of physically moving (such as patterns of visual motion across the whole visual field) that specified self-motion. Visual motion produced by self-motion is generally called visual (or optic) flow. The specific pattern of visual flow at the eye depends both on the self-motion of the observer and on the spatial structure of the environment. Gibson showed that visual flow can be informative about both at the same time.

This article examines the perception of self-motion, with a theoretical emphasis on the idea that, in the control of action, perceptual precision (the fineness of discrimination among actual values of a variable) is more important than perceptual accuracy (direct correspondence between the perceived and actual value of a variable). For example, after adapting to prism glasses for a few minutes, one can hammer a nail quite effectively even though the apparent position of the nail remains offset by several centimeters. Good performance requires only that the felt position of one's hand become precisely aligned with the visual location of the nail (Harris, 1980). Regarding the perception of locomotor self-motion, we have found evidence that systematic distortions of perceived visual speed during walking enhance perceptual precision in the measurement of visual speed—that is, flow speeds near to walking speed are best discriminated from one another when one is walking. The distortion of perception and the concomitant improvement in perceptual discrimination are both predicted by a rather simple model of sensory recoding that applies when two or more signals (like walking and visual motion) are highly correlated in experience. Discussion of how this may generalize to other kinds of perceptuomotor behaviors will be presented in the conclusion. We first consider the multisensory nature of the spatial sense.

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CURRENT DIRECTIONS in Psychological Science

WALKING WHILE BLINDFOLDED

A great deal of evidence has accumulated indicating that people are quite sensitive to the information in visual flow that specifies the direction and distance traveled (e.g., Lappe, Bremmer, & van den Berg, 1999; Warren & Hannon, 1988) and that visual-flow speed influences walking speed (Mohler, Thompson, Creem-Regehr, Pick, & Warren, 2007). What is even more surprising is how good people are at keeping track of how far they have walked even when they are blindfolded (Loomis, Da Silva, Fujita, & Fukusima, 1992). Just as one can gaze at a distant target, close one's eyes, and still point to it quite accurately (try it), most people can look at a distant target, close their eyes, and walk fairly accurately to it (though they were previously unaware of their ability to do so). Performance is good even when the target is more than 20 meters (70 feet) away (Rieser, Ashmead, Talor, & Youngquist, 1990).

The basis for this remarkable ability does not appear to derive solely from vestibular stimulation, but probably also from the motor activity of walking itself (Mittelstaedt & Mittelstaedt, 2001). Walking is such a common activity and our step-sizes are so standard, that even if our brain just counted steps, it would be able to measure distances very accurately (Durgin, Reed, & Tigue, 2007). This is not to say that visual information is ignored. Rather, our vast experience of the relationships between visual flow, vestibular stimulation, and the actions involved in walking means that the presence of two of these can predict the third.

Evidence for this view comes from studies in which the speed of visual flow is either artificially exaggerated or minimized during walking or running (e.g., Mohler, Thompson, Creem-Regehr, Willemsen, et al., 2007). The relationship between perceived self-motion and motor action can be altered using large-scale simulators to deliver different rates of visual motion during walking (see Fig. 1). Such manipulations affect the perception of distance traveled later during blindfolded walking. As an extreme example, exposure to treadmill running (where there is no visual flow) for as little as 20 seconds temporarily alters the internal guidance system so that people walk too far when they try to walk on solid ground to a target while blindfolded (Durgin, Pelah, et al., 2005). The idea is that your sense of self-motion from using your legs to propel yourself has been reduced because you made no progress while on the treadmill. You will now walk too far on solid ground when your eyes are closed because your brain expects that you are making less progress than you really are (Rieser, Pick, Ashmead, & Garing, 1995).

SEEING VISUAL FLOW WHILE WALKING

We have seen that visual-flow information is important to controlling action both immediately, as feedback, and in the longer run, as training information for the unconscious self-motion system. Our next surprise is that the perception of visual flow is distorted during walking.

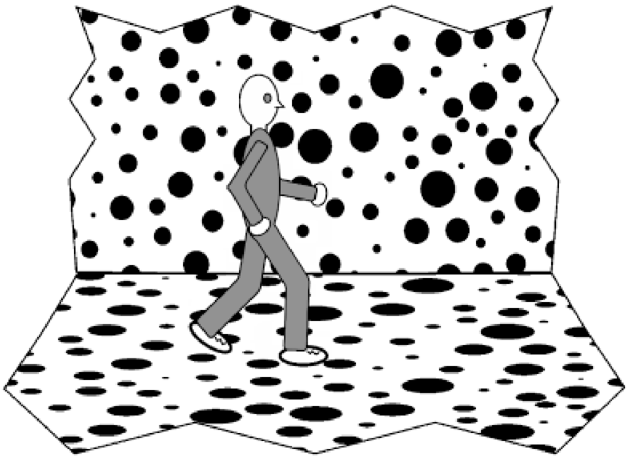

Fig. 1. Person walking in a simulated environment. The spots on the wall(s) and floor would normally flow past the walker as he or she walked forward (visual flow), but in a simulator they can be made to move faster or slower than they normally would. If the spots are taken away, no visual speed is present. A person in a speed discrimination experiment would be presented with one set of spots moving at one speed (relative to the person) and, after a short blank, a second set of spots, moving at a different speed. The person's task is to judge which speed was faster. Visual-flow speeds that are near walking speed look slower and are easier to tell apart when you are walking than when you are standing, though the speeds in the retinal image are the same.

For many years it has been known that the perception of visual flow is reduced during self-motion. It was thought that this reduction was probably useful for maintaining the perception of a stable world (Wallach, 1987). After all, the world really is stationary when we are walking, so seeing it as moving would be a mistake, in a sense. But there is a difference between seeing the world as moving and being able to see the visual flow produced by one's own movement. Is the reduced speed in visual flow that we experience based on a separate representation from the one that helps to measure speed of self-motion?

The reduction of visual flow has only recently been quantitatively investigated for walking observers (Durgin, Gigone, & Scott, 2005). It has been shown to approximate simple subtraction that is related to one's speed. If you are walking along a hallway, you can notice (if you look for it) that the hallway seems to be flowing past you. But the visual speed you will seem to experience is actually less than you would experience if the hallway were actually moving past you while you remained stationary (Durgin, Gigone, et al., 2005). The relationship between the perceived speed of the hallway and your own speed of walking turns out to conform to an equation suggested originally by Horace Barlow to account for interactions within a single sense. The theory behind the equation was developed to formalize improvements in one's perceptual discrimination that can arise when two different sources of visual information are correlated (Barlow & Földiák, 1989). However, this theory can also apply to the correlations between vision, vestibular signals, and the action of walking because of the causal relationships that bind these together.

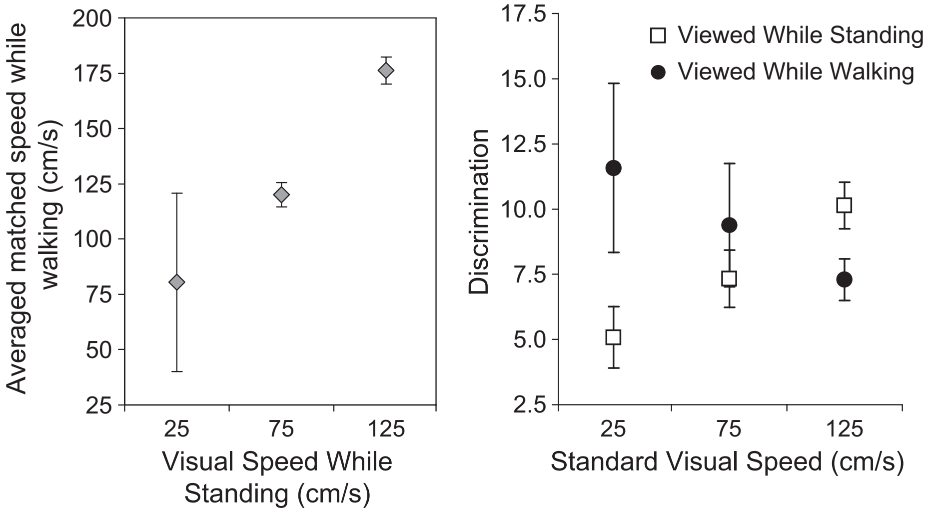

Fig. 2. Accuracy and precision results from Durgin and Gigone (2007; Experiment 1). The graph on the left (accuracy) shows average visual-flow speeds while walking, plotted against their perceptually matched visual-flow speeds while standing. A moving simulated hallway was presented via an immersive head-mounted display for a few seconds while the participant walked at normal walking speed (about 125 centimeters/second, or 2.8 miles per hour), and then another was presented via the same display while the subject stood still. Subjects indicated which interval had seemed to be visually faster; a psychometric function was used to find the point of subjective equality for each participant. On average, speeds presented while walking had to be about 50 centimeters/second (1.1 miles per hour) faster than those presented while standing for the speeds to appear subjectively equal. The graph on the right (precision) shows discrimination thresholds for visual-flow speed as a function of presented-flow speed while walking (filled circles) and while standing (open squares). The task in this case was to judge which was the faster of two successive flow speeds presented either both while walking or both while standing still. Discrimination thresholds represent the average magnitude of speed difference at which discrimination was correct 75% of the time. While walking, discriminating between low flow speeds is impaired (larger threshold) compared to standing, but discriminating between flow speeds approximately appropriate to walking is enhanced (smaller threshold). If locomotor control systems are monitoring for discrepancies between anticipated and experienced visual-flow rates, the enhanced precision would be of use to them, whereas the net inaccuracy is of no consequence.

Barlow's theory simply states that when two perceptual dimensions are correlated, they can each be recoded to take into account the information provided by the other. In the terms of Barlow's equation, perceived visual-flow speed would be equal to actual visual-flow speed minus some proportion of perceived self-motion speed:

$$\begin{aligned}&\text{Visual Velocity (perceived)}\\&\quad = \text{Visual Velocity (actual)} - \text{K (a constant)}\\&\qquad \times \text{Felt Velocity (perceived nonvisually)}\end{aligned}$$

The functional goal of such recoding is to make more efficient use of neural coding space—that is, the structures in the brain used to represent visual-flow velocity.

The distortion of visual flow while walking is a bit like resetting the zero point of the coding space so that expected velocities are smaller than they would otherwise be and can therefore be represented more precisely. By reducing the motion signal from visual flow while walking, the visual system can improve its ability to encode the remaining motion signal more precisely because small differences in speed are proportionally larger compared to the absolute perceived speed if the overall magnitude of perceived speed is reduced. Empirically, we have found that the assessment of visual-flow speed (at least for those speeds appropriate to walking) is measurably more precise while walking than it is while standing still (Durgin & Gigone, 2007). Typical data are shown in Figure 2. Although this may seem a bit like magic at first blush, it is important to remember that the information used to "slow down" the visual motion (nonvisual information about one's walking speed) is not part of the visual motion signal, though it is causally related to it. What this means is that nonvisual signals about self-motion can cause the visual system to, in effect, change gears in order to be better able to measure the exact visual feedback it is receiving. The act of moving creates a special perceptual context within which deviations from expected visual speeds can be better evaluated.

WHY IS PERCEPTUAL DISCRIMINATION SO IMPORTANT?

For most of us, perceptual processes are the least of our concerns. We see the doorway; we walk through it. We see the glass; we pick it up. These actions seem effortless. But under the hood of our perceptual systems lies millions of years of evolutionary tuning that has developed sophisticated processes for making precise sensory discriminations that are self-adjusting and adaptive. For the perceptual control of action, precise discrimination is more important than accuracy. Consider walking through a doorway (Warren & Whang, 1987). The crucial information concerns the size of the doorway relative to your body, not the absolute size of the doorway, per se. You could be wrong about both the true size of the door and the size of your body and still make excellent decisions about which doorways are passable.

When you pick up a glass, does your brain have to know where the glass is exactly, or does it really only need to compare two quantities: the visual location of the glass and the anticipated location of the intended reach? Prism adaptation indicates the latter (Harris, 1980). If motor actions are normally paired with visual consequences (and most of them are), then learning the visual consequences of actions (and being able to predict them with precision) should allow a person to produce a motor action to suit a visual intention based on a relative comparison—like the comparison of the door and the body—rather than an absolute one. Skill at relative judgments can underlie the coordination between perception and action because action and perception can function with respect to the same coordinates effectively even if these coordinates are distorted.

In practice, the coding of a motor action could (and probably must) use a common unit with visual processing, but the main point to recognize is that these units can be arbitrary and do not need to be consistent across different contexts. What is most important is that they be precise. Thus, the slowdown of apparent visual speed during self-motion is not a problem for a system trying to coordinate action and vision. Rather, such a slowdown is predicted by recoding theory because it allows for greater precision of visual judgment in the comparison process. The arbitrary units of (ultimately neural) coding can be distributed more finely across the range of likely values of visual motion if that range is reduced.

The cost of this recoding is that, while walking, we become poor at discriminating among very low (unlikely) speed values, as shown in the right panel of Figure 2. Indeed, using a simulator to project a very slow speed of visual flow during walking will produce the impression that there is no motion at all, even though the motion would be clearly visible while standing still (Durgin, Gigone, et al., 2005). Such slow visual speeds are so unlikely in the course of normal walking that the cost of misjudging them is far outweighed by the clear benefits to the coordination of perception and action achieved by shifting the units of visual flow speed during self-motion into the range where they are most useful.

FUTURE DIRECTIONS IN MULTISENSORY COORDINATION

Documenting apparent trade-offs between precision and accuracy in the coding of visual speed may help foster progress in understanding a broad variety of tasks involving the coordination of action and perception. Our de-emphasis of accuracy contrasts with views that have been dominating our field recently. Over the past 10 years, a theory of optimal sensory integration has been developed, based on using Bayesian statistical theory to explain the best way to combine different sources of sensory information. That theory is focused on increasing both sensory precision and accuracy by combining different types of sensory information (e.g., Ernst & Banks, 2002). Over the same time period there has been an explosion of research around the idea that conscious perceptual experience is somehow separate from the ostensibly more accurate (i.e., absolute) perceptual processing used to control action (e.g., Milner & Goodale, 1995).

Our focus here has been that a distortion in conscious perceptual experience (a reduction in perceived visual speed) is accompanied by a beneficial effect on sensory discrimination in a way that is different from classical cue-combination theories of sensory integration. In this new theory, perceptual systems can reduce uncertainty by using correlations between perception and action to rescale the coding space in which they operate—to tune perception to the motor context in which it occurs. Moreover, rather than emphasizing the need for accurate absolute metrics for action, the new theory suggests that the precision of the relative metrics of perception and motor action are much more important.

Walking is one example of a highly stereotyped and common activity that produces highly predictable visual and vestibular perceptual signals. But there are many common motor activities (like talking) that tie together perception and action in ways that may also afford this kind of tuning. The reason that practice may be so effective in activities involving perception and action—from musicianship to athletics—may include the possibility of rescaling perceptual experience in order to make perceptual discrimination more precise and thus afford more precise coordination in the control of action.

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