Distance Perception

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ABSTRACT—*Distance perception seems to be an incredible achievement if it is construed as being based solely on static retinal images. Information provided by such images is sparse at best. On the other hand, when the perceptual context is taken to be one in which people are acting in natural environments, the informational bases for distance perception become abundant. There are, however, surprising consequences of studying people in action. Nonvisual factors, such as people's goals and physiological states, also influence their distance perceptions. Although the informational specification of distance becomes redundant when people are active, paradoxically, many distance-related actions sidestep the need to perceive distance at all.*

KEYWORDS—*perception; vision; distance; action*

Many of the oldest questions in psychology deal with perception—the means by which people know the world—and distance perception has been one of the central conundrums. The question is typically posed as follows: Given a two-dimensional retinal image of a distant object, how can one perceive the distance between oneself and the object? Stated this way, the perceptual system appears to be confronted with a hard, perhaps impossible, problem. A way out of this difficulty is to consider the environmental and bodily contexts in which the retinal image is embedded.

In fact, people are fairly accurate in perceiving distances. Studies conducted in natural environments find that perceived distance tends to be slightly underestimated when assessed by verbal reports or visual matching tasks, whereas another dependent measure, blindwalking, tends to be more accurate (Loomis, da Silva, Fujita, & Fukusima, 1992). In blindwalking, people view a target and then attempt to walk to its location while blindfolded.

The research literature on distance perception is voluminous and dense. I will not attempt to review it in this article. Instead, I will develop current views of distance perception by taking the core problem—how to derive distance from a two-dimensional retinal image—and wrapping this problem in layers of context that relate to both the perceiver's body and the natural environment in which perception takes place.

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FROM IMAGES TO BODIES ACTING IN NATURAL ENVIRONMENTS

The Image

Berkeley (1709/1975) noted that a point in space projects to a point on the retina and that this retinal projection conveys no information about the point's distance from the eye (see Fig. 1). From this, Berkeley concluded that distance perception could not be based on optical information alone. It is now recognized that, in complex natural environments, there is far more information about distance than could be gleaned from Berkeley's situation of observing a point in a void.

The Image in an Eye

The retinal image exists in an eye having a sizable pupil. A luminous point in space would illuminate the whole pupil and thereby project an area of illumination (not a point) on the retina, were it not for other optical structures. These structures, the cornea and lens, bend light so that rays converge to a point on the retina. The lens changes its curvature when focusing on objects at different distances. This process, called *accommodation*, informs the perceptual system about distance and is effective for close objects.

Two Eyes

People, of course, have two eyes, and each eye must be directed at the object of regard. The gaze angles for the eyes define *convergence*, which effectively specifies distance for near objects. In addition, each eye has a slightly different perspective on the scene, and this is the basis for stereo vision.

Eyes in a Body

The eyes exist within a body and this fact has profound consequence for distance perception. Notice first that, for a standing observer, the eyes have a constant elevation above the ground. In many situations there exists optically specified distance information that can be scaled to one's eye height (see Fig, 2).

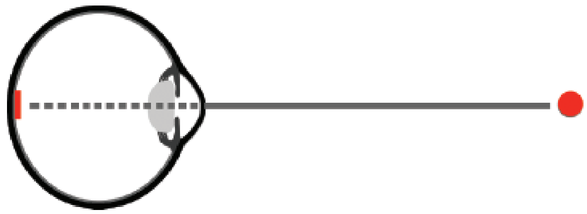

Fig. 1. The problem of distance perception distilled to its minimal representation. A point in space projects its image into the eye. The retinal image contains no information about the distance of the point from the eye.

Fig. 3. Texture gradient. As the ground plane recedes into the distance, its texture, which in this situation consists of tiles, becomes compressed and denser.

The Body in the Natural Environment

The natural environment presents nothing like the situation that Berkeley described; Berkeley discussed a point being observed in an otherwise empty environment. The natural environment consists of a ground plane, which is typically littered with objects. While the distance to a point viewed in a void is not optically specified, the distance to an object on the ground is.

Gibson (1979) showed how distance perception is informed by optical variables that are available to people when they are situated in natural environments. In contrast to the way Berkeley described the distance-perception problem—as an extent through empty space (Fig. 1)—Sedgwick (1986), elaborating on Gibson's approach, represented the problem as depicted in Figure 2. Here it is shown that if an object and perceiver are both located on level ground, then the distance to the object is specified by optical variables. The visual angle α is formed by the gaze angle to the object relative to the straight-ahead view coinciding with the horizon, or it can be derived from the gaze angle relative to vertical. Given the visual angle α and the observer's eye height, I, then the distance, d, to the object is given by the equation $d = I/\tan\alpha$. Expressed in words, the distance to the object is a function of its angular elevation scaled to the observer's eye-height.

The importance of this formulation of the distance-perception problem cannot be overstated, because it shows that, in most viewing situations, the distance to an object is directly specified by visual angles inherent in optical information. For this formulation to work, objects and observers need to be on the ground and the ground needs to be relatively level.

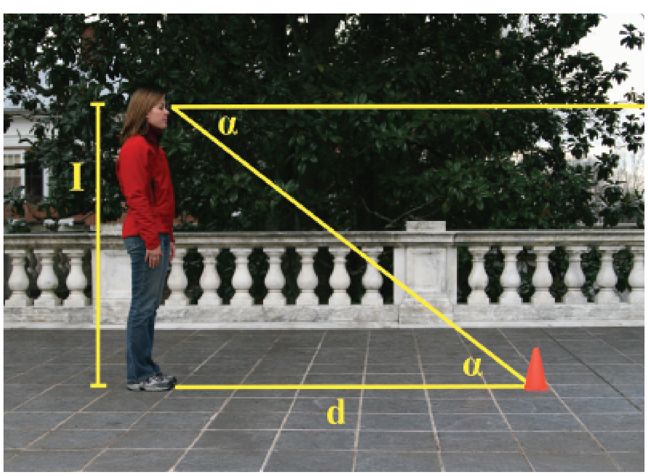

Fig. 2. A person viewing a cone situated on the ground. The distance of the cone from the observer, d, is specified by the visual angle, α, relative to her eye height, I, by $d = I/\tan\alpha$.

Gibson (1979) also noted that the natural environment consists of surfaces having different textures; textures project to the eye in lawful ways that relate to distance (Sedgwick, 1986). As illustrated in Figure 3, the projected texture of the ground surface—notice the tiles in the figure—becomes increasingly compressed as it gets farther away, thereby forming a gradient of density, which is informative about distance.

The Body in Action

An observer's movement through the environment produces a continuous change in perspective, which is highly informative about distance. Figure 4 depicts a bird's-eye view of an observer who is initially, at T_1, looking at an object that is straight ahead of her. As she moves to the left, the visual angle to the object, β, increases to her right. Between T_1 and T_2, the observer will have traversed a certain distance, d_t. The initial distance to the object, d, is given by the equation $d = d_t/\tan\beta$. Expressed in words, the distance to the target is a function of the distance traveled and the change in the visual angle to the object.

Interim Summary

So far I have shown how distance perception becomes increasingly well specified as aspects of the body and environment are brought into the perceptual situation. It is very important to note, however, that nothing has been said about how the perceptual system responds to this available information, what its sensitivities might be, or how different sources of distance information are combined. These are tough problems, which are reviewed extensively elsewhere (Cutting & Vishton, 1995; Proffitt & Caudek, 2002; Sedgwick, 1986).

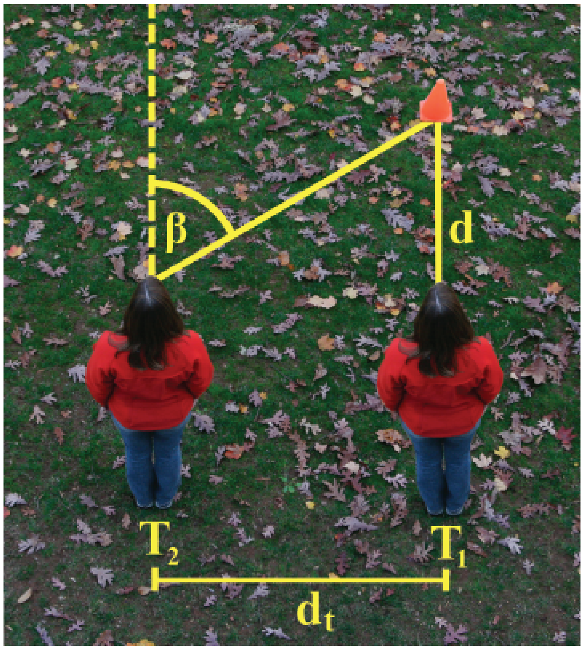

Fig. 4. Motion perspective. The distance to the cone, d, is specified by the change in the visual angle to the cone, β, and the distance, d_t, that the observer moved by $d=d_t/\tan \beta$.

PURPOSIVE PERCEPTION

Embodied Perception

Distance perception is influenced by the body in many ways. I have shown how distances are scaled to the body's stature (eye height) and informed by the optical consequences of locomotion (motion perspective). Apparent distances are also influenced by the energetic costs associated with performing distance-relevant actions, the observer's purposes, and the behavioral abilities of the observer's body (Proffitt, 2006).

Objects appear farther away as the energy required to act on them increases. Viewing a target while wearing a heavy backpack causes its distance to appear greater relative to when no backpack is worn (Proffitt, Stefanucci, Banton & Epstein, 2003). When people throw balls to targets, targets appear more distant when the balls are heavy than they do when the balls are light (Witt, Proffitt, & Epstein, 2004). An especially compelling instance of energetic influence on distance perception occurs when people walk on a treadmill. Walking on a treadmill produces an adaptation in which the visual–motor system associates forward-walking effort with remaining stationary. Given that the system learns that effort is required to go nowhere, it follows that, after treadmill adaptation, more effort will be required to walk a prescribed distance. This anticipated increase in walking effort evokes an increase in apparent distance: Objects appear farther away after walking on a treadmill (Proffitt et al., 2003).

Purpose is also critical; effort's influence on apparent distance is specific to the intended action. Walking on a treadmill influences the apparent distance to an object only if people anticipate walking to it. If, after a period of treadmill walking, a person views a target with the intention of throwing a beanbag to it, then its apparent distance is unaffected by the treadmill-walking experience (Witt et al., 2004). Similarly, throwing a heavy ball to a target influences its apparent distance only if people anticipate throwing to it again, not if they intend to walk to it (Witt et al., 2004). These studies show that people view intervening distances as "walkers" or "throwers" and that perceived distances are influenced by the energy required to perform these actions.

The extent of one's reach defines a special region, called near or personal space (Cutting & Vishton, 1995). This extent can be lengthened by holding a tool, and this expansion of near space influences perceived distance. Witt, Proffitt, and Epstein (2005) showed that target locations, which were within reach when holding a tool (a conductor's baton) but out of reach without it, appeared nearer when the baton could be used to touch the targets. Objects within reach have a unique immediacy; they can be touched. Holding a tool extends reach and thereby confers an immediacy and closeness to those objects that become touchable through the tool's use.

Visual Control of Action

Common sense suggests that many visually guided behaviors rely on distance perception. When driving, for example, we may notice that the car in front of us has stopped and that the distance between ourselves and this car is rapidly decreasing; consequently, we brake to avoid a collision. Such a situation appears to be a case in which distance perception is of paramount importance, but this may not be so.

Lee (1976) noted that a time-to-contact variable that relates the visually projected size of the stopped car to its rate of expansion in the field of view could be effectively used to control braking without there being a need to know or perceptually represent the distance to the stopped car. There is evidence that people utilize this variable when braking (Yilmaz & Warren, 1995). What is important for our discussion is that when performing actions on a distance, such as braking to avoid a collision, people may rely on optical variables that bypass the need to take distance into account.

Another situation in which distance perception may be sidestepped is that of baseball outfielders catching fly balls. Common sense suggests that, to catch a fly ball, outfielders must know where the ball is going to land and that knowing the distance to this location is an important component in getting there effectively. One account suggests, instead, that outfielders use a visual-control heuristic in which they need only run so that the path of the ball maintains a linear trajectory relative to their eyes (McBeath, Shaffer, & Kaiser, 1995): If the trajectory curves, then the fielder must run with a speed and in a direction that nullifies the curvature. If fielders can run so as to maintain the ball's projected linear trajectory, then they will arrive at the location where it can be caught without ever representing where they were going.

FUTURE DIRECTIONS AND CONCLUDING REMARKS

For moving observers in natural environments, distances are well specified; requisite information abounds. I have provided only a scant description of the optical and ocular-motor information that is available. Far less is known about how this information is actually used; in this regard, perhaps the most difficult problem is determining how information from different sources is combined. An especially thoughtful discussion of this issue was provided by Cutting and Vishton (1995), who noted that the utility of different informational sources depends on distance. Accommodation and convergence, for example, are most useful for near distances, whereas *occlusion* (the obscuring of objects by other objects) is equally useful for distances near and far.

Recent research has shown that apparent distances are influenced by the perceiver's behavioral potential and the energetic costs associated with intended actions. That perception is subject to such influences raises the possibility that other factors may be influential as well. What might these factors be?

Ongoing research from our lab indicates that emotional and social factors are also influential (Proffitt, 2006). For example, in her dissertation research, Stefanucci (2006) is finding that, when people look down from a high balcony, they hugely overestimate the distance to the ground. Moreover, the magnitude of this overestimation is positively correlated with people's fear of heights. Other research indicates that the distance to objects within personal space is influenced by social ownership (Schnall et al., 2005). People at an outdoor cafe were approached and asked to judge the distance to a soda can placed on the table within their reach. In one condition, the can had been given to the participants—it belonged to them—whereas in the other condition, the can belonged to the experimenter. Participants perceived the can to be closer when it belonged to the experimenter—and had invaded their personal space—than when it was their own soda.

Another unresolved question deals with the role of distance perception in the visual control of action. I discussed cases in which the visual guidance of action has been found to rely on control heuristics that bypass the need to represent distance. In these cases, there seems to be a mismatch between the information that is guiding people's actions and the informational bases for their explicit awareness. Baseball players, for example, are oblivious to the nature of the visual heuristics that they use when catching fly balls. Instead, their awareness is of the spatial layout of the field, the flight of the ball, and the fact that they are running to catch it. Being aware that they are running with the intent to catch the ball engenders an assumption that they are also aware of the location to which they are running. This location, however, is not specified by the visual heuristic that is controlling their running.

One way of reconciling this mismatch between the visual information that guides actions and that which supports explicit awareness is to suppose that there exist functionally and anatomically distinct visual systems (Goodale & Milner, 2004). By such an account, the visual guidance system controls immediate actions over short extents of time and space, whereas explicit awareness is responsible for long-term planning. The two-visual-systems account is controversial and should continue to motivate research for some time to come. At stake is no less then the definition of perception and its relationship to consciousness. Should the unconscious, visual control of action be considered an instance of perception? How does one distinguish between behaviors that are guided by perception from those that are controlled by visual information for which there is no conscious access? These are fundamental questions of relevance throughout psychology.

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