Embodied Perception and the Economy of Action

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ABSTRACT—***Perception informs people about the opportunities for action and their associated costs. To this end, explicit awareness of spatial layout varies not only with relevant optical and ocular-motor variables, but also as a function of the costs associated with performing intended actions. Although explicit awareness is mutable in this respect, visually guided actions directed at the immediate environment are not. When the metabolic costs associated with walking an extent increase—perhaps because one is wearing a heavy backpack—hills appear steeper and distances to targets appear greater. When one is standing on a high balcony, the apparent distance to the ground is correlated with one's fear of falling. Perceiving spatial layout combines the geometry of the world with behavioral goals and the costs associated with achieving these goals.***

Visual perception is not solely a visual process. What one sees in the world is influenced not only by optical and ocular-motor information, but also by one's purposes, physiological state, and emotions. Perceptions are embodied; they relate body and goals to the opportunities and costs of acting in the environment. Here are some examples: Under constant viewing conditions, the apparent incline of hills increases when people are tired or encumbered by wearing a heavy backpack; hills also appear steeper to people who are in poor physical condition or who are elderly and in declining health, compared with those who are young, healthy, and fit. Similarly, apparent distance increases when the observer is encumbered by a backpack or throwing a heavy ball. When one is standing on a high balcony, the apparent distance to the ground is positively correlated with one's fear of heights.

That visual perception should be influenced by such nonvisual factors may seem odd or wrongheaded. Most current accounts of vision begin with the optical information available to the eye and suggest ways in which this information is detected and transformed into visual perceptions. Many visual scientists view vision as a modular, encapsulated process that is unaffected by nonvisual factors (Pylyshyn, 2003). Such approaches have had great success, but because of their exclusive focus on optical determinants for visual perception, I believe them to be incomplete.

Evolutionary pressures have made human visual perception what it is, and from an evolutionary perspective, even an account of the anatomical structure and function of the human eye must include social, emotional, and other nonvisual influences. The human eye is a variant of the simple chambered eye possessed by all vertebrates, as well as some nonvertebrates, such as scallops, spiders, and squid (Land & Nilsson, 2002). As with all animal eyes, the particulars of the human eye reflect selection pressures that relate its anatomy to the organism's way of life (Land & Nilsson, 2002). Included among these pressures are not only demands related to sensitivity and spatial resolution, but also pressures that have nothing to do with optics. Consider, for example, the fact that, for anatomical reasons, humans show more whites of their eyes (sclera) than do other animals; the other great apes show almost none (Kobayaashi & Kohshima, 1997). In addition, humans are the only primate species to have a white sclera; the sclera of other primates is colored (Kobayaashi & Kohshima, 1997). It is thought that this display of a large area of white sclera came about as a result of evolutionary selection pressures that favored the social advantages of being able to see where other individuals are looking (Emery, 2000). Pupil size itself is influenced by such visual and nonvisual factors as ambient light, accommodation, arousal, and cognitive workload (Beatty & Lucero-Wagoner, 2000). The increase in pupil size that accompanies arousal decreases the range of depth focus, which impairs resolution. Another anatomical feature of the human eye—a feature that is common to all mammalian eyes—is the presence of photoreceptive ganglia cells. (Most nonmammals have these cells located in their heads, and in such cases, the cells detect light passing through the skull; Foster & Kreitzman, 2004). These cells are not the rods and cones that participate in vision; rather, they detect light intensity over the whole retina and project to a structure in the hypothalamus called the suprachiasmic nucleus, which is the master biological

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clock capable of being entrained to the light/dark cycle of the day (Provencio et al., 2000). As these examples show, the human eye is not solely an organ for vision. It has also evolved for social communication, for maintenance of biological rhythms, and to respond to internal emotional states.

Given that the eye's structure and functioning are influenced by visual and nonvisual evolutionary selection pressures, it seems plausible that visual perception reflects such pressures as well. In the remainder of this article, I discuss evidence in support of this claim. In particular, I argue that visual perception promotes survival by making people aware of both the opportunities and the costs associated with action.

SURVIVAL AND THE ECONOMY OF ACTION

A principal law of survival is that energy consumption must exceed energy expenditure. This law implies an economy of action in which energy must be conserved; over time, expenditure must not exceed consumption. For example, a predator cannot expend more energy in catching prey than it acquires by eating them. All actions expend energy, and this expenditure must be managed effectively.

The principal contention of this article is that the economy of action is formative in visual perception. What one sees in the world is determined largely by the geometry of surface layout as revealed in optical and ocular-motor variables. Visual psychophysics has a great deal to say about how the environment's perceived layout is specified by these variables. However, visual perception is mutable in ways that relate the opportunities for action to the need to behave in an energy-efficient manner. For example, donning a heavy backpack makes hills look steeper and objects appear farther away. These examples show that perceived slant and distance relate the distal properties of the environment to the energetic costs of locomotion—the possibility and costs of locomotion are coupled.

Most of the research conducted by my coworkers and I has dealt with the perception of the ground, which has two parameters, orientation and extent. The orientation of the ground is called geographical slant, which is the ground's angle of inclination relative to the horizontal. The extent to a target from an observer is called egocentric distance. I discuss the perception of these two fundamental aspects of the environment in turn.

SLANT PERCEPTION IN THE ECONOMY OF ACTION

Most of our slant-perception studies were conducted outdoors and employed various hills located on the grounds of the University of Virginia. A few studies also used virtual environments (VEs) presented in head-mounted displays (HMDs). Typically, participants stood at the base of a hill, although in some studies they viewed the inclines from the top. Each hill had a sufficiently long extent such that when participants stood at its base, the top of the hill was well above their eye height. While looking at the hill, participants were asked to make three slant assessments, the order of which was counterbalanced across participants. For the *verbal* assessment, participants verbally estimated the hill's slant in degrees. They were told that the horizontal ground plane is 0° and that a vertical surface is 90°, and were then asked to estimate the inclination of the hill before them. The second assessment was a *visual* matching task. For this task, participants were handed the disk depicted in Figure 1. The disk represented the hill viewed in cross section. While facing the hill, participants adjusted the pie-shaped segment of the disk to be equivalent to the slant of the hill. Finally, in the *haptic* matching task, participants placed their hand on a palmboard that swiveled (see Fig. 2). They adjusted the palmboard by feel, matching the board's felt orientation to the hill's incline. This visually guided action was performed while looking at the hill, not at the palmboard.

Slant Is Overestimated in Explicit Awareness

A principal finding of these studies was that the verbal and visual measures exhibited huge overestimations, whereas the haptic measure yielded relatively accurate assessments (Proffitt, Bhalla, Gossweiler, & Midgett, 1995). For the verbal and visual measures, 5° hills were judged to be about 20°, and 10° hills were judged to be about 30° (see Fig. 3).

The verbal and visual tasks tap into an explicit awareness in which hills look much steeper than they are. When we told participants that the 5° hill that they had just judged to be 20° was only 5°, they often were incredulous and suspected that we were attempting to deceive them. A 30° grassy hill looks formidable, and rightly so. It is about the limit of what people can

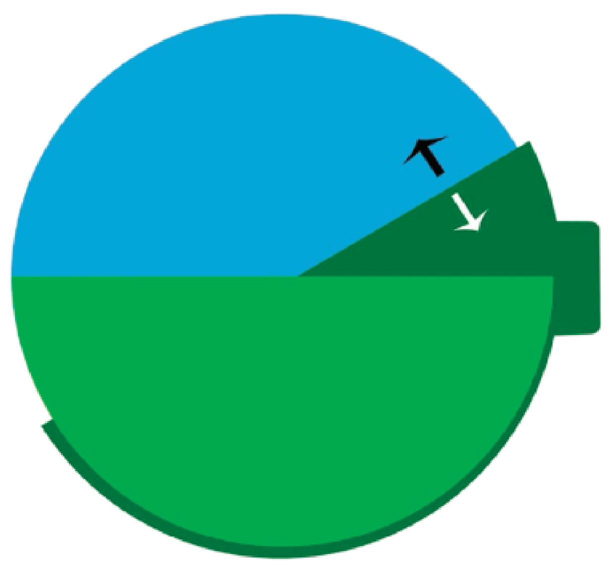

Fig. 1. The visual matching device for slant estimation. Participants rotated the dark green semicircle so as to make the pie-shaped segment appear to have an angle equivalent to the cross section of the viewed hill. The disk was about 15 cm in diameter.

Fig. 2. A participant using the haptic device (palmboard). Her task was to adjust the board to be parallel to the incline of the hill without looking at her hand.

ascend without using their hands, and it is too steep to walk down with a normal gait. In Virginia, a mountainous state by East Coast standards, state law prohibits any state-owned road from having a slant of more than 9°. When asked, people tell us that these steepest roads must be at least 25 to 30°.

In contrast to the verbal and visual tasks, the haptic task involves a visually guided action. Haptic responses are accurate, and as I discuss later in this section, they are not subject to the nonvisual influences of effort that affect explicit awareness.

An oft-expressed concern about the overestimation findings is that "maybe people are unskilled and biased in their ability to report angles in terms of degrees." We have an answer for this concern. After participants made their slant judgments, we asked them to set the disk to a wide variety of angles that were given verbally in degrees. For example, the experimenter would say, "Set the disk to 45°." Participants performed this task with high accuracy (Proffitt et al., 1995). People are good at knowing what angles, expressed in degrees, look like.

Another objection is that "perhaps people are just unskilled and biased in translating the hill's pitch into roll." That is, the hill was viewed head-on, but the visual matching task depicts a cross-section perspective. To address this concern, we ran a study in which participants viewed hills in cross section. We found no difference, relative to head-on viewing, for any of the three measures (Proffitt, Creem, & Zosh, 2001). This result is quite remarkable because in one of the viewing conditions, accuracy could be achieved by aligning the horizontal on the disk with the horizontal surfaces of a visible parking garage and then aligning the top of the pie-shaped segment with the surface of the hill (see Fig. 4). No one did this. Moreover, we recently ran a study in which participants judged the hill's incline using a disk with only a diameter line drawn across it (see Fig. 5). When asked to set the orientation of this line to that of the hill viewed in cross section, participants did not simply align it with the hill's

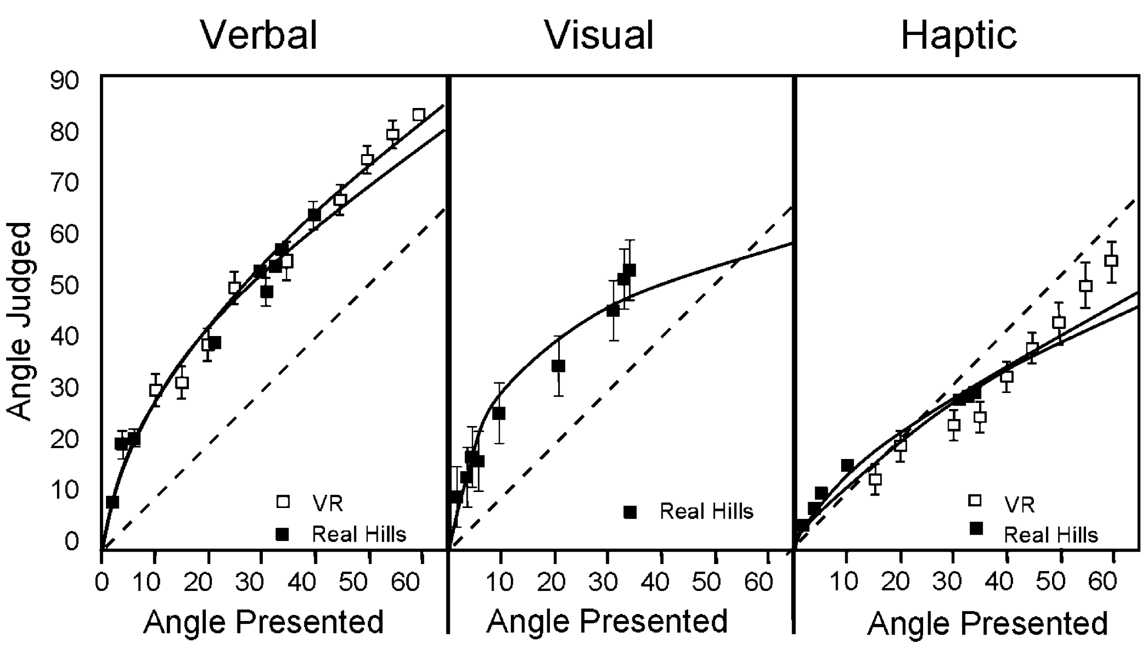

Fig. 3. Perceived angle as a function of true angle (from Proffitt, Bhalla, Gossweiler, & Midgett, 1995). Perceived angle was measured verbally, visually, and haptically. The verbal and haptic measures were employed for both real and virtual-reality (VR) hills. The visual measure could not be employed in VR, so the range of hills was restricted. The dashed lines correspond to accurate performance, and the error bars indicate ±1 *SEM*.

Fig. 4. A hill viewed in cross section.

surface; rather, they continued to overestimate the hill's slant by about the same magnitude as we had found for other measures of explicit awareness (Witt & Proffitt, in press).

Having been convinced that people do, indeed, overestimate geographical slant in their explicit awareness, people sometimes raise a new objection, that being, "So what? Explicit awareness does not guide action. The visually guided haptic measure is accurate, so there is no real pressure for consciousness to be accurate in the first place. Explicit awareness is useless." People say such things to me; however, I disagree.

Explicit Overestimation of Slant Is Useful

Overestimation of slant promotes a heightened sensitivity to differences in the small inclines that people can actually traverse. Explaining why this is so requires a little discussion of

Fig. 5. A participant using the simple disk to judge the slant of a hill viewed in cross section.

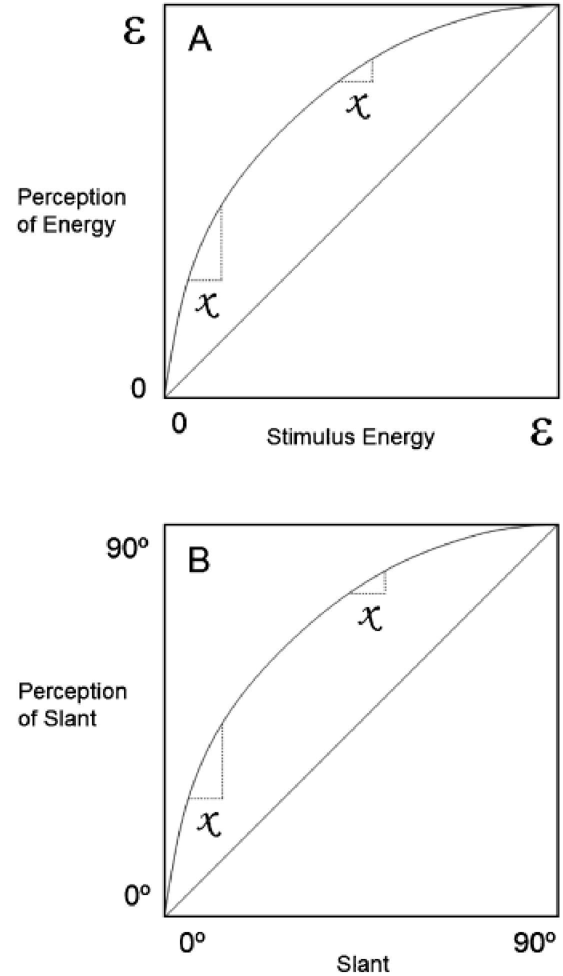

Fig. 6. Idealized psychophysical functions for perception of energy (a) and slant (b). Both graphs show that the perception of stimulus magnitude is a decreasing function of the actual stimulus magnitude. The dashed lines show that as x increases, equal changes in x are associated with ever-smaller changes in y.

psychophysics. Figure 6a depicts a psychophysical function. On the horizontal axis is the magnitude of stimulus energy, and on the vertical axis is the perceived magnitude of this energy. For many stimulus energies, such as light, apparent intensity is a decelerating function of stimulus intensity. (This relation can be expressed as a psychophysical power function with an exponent less than 1.) A virtue of such a function is that sensitivity is inversely related to the overall magnitude of the background energy. With respect to light, for example, a dark-adapted person can detect the presence of only a few photons of light in a completely dark environment; however, it requires orders of magnitude more light to detect a change in brightness at high ambient light levels.

Figure 6b shows an idealized psychophysical function for perception of geographical slant. The function is decelerating, causing sensitivity to be best for small slants. As depicted in this figure, two equal changes in distal slant evoke different magnitudes of change for perceived slant, with the magnitude of change being greater for the smaller slant. This is useful, because the difference between, for example, a 5° hill and a 6° hill is of considerable importance when planning locomotion, whereas the difference between, say, a 65° cliff and a 66° cliff is of no behavioral significance. It is important to note that people are generally accurate at telling whether the ground is sloping down or up, so they are correct when judging 0°. Similarly, for reasons related to discontinuities in such optical variables as texture compression, people can tell whether a near-vertical surface is inclined toward or away from them; thus, they estimate 90° angles correctly. If the psychophysical function depicted in Figure 6b is anchored at 0° and 90° and is decelerating, then overestimation must necessarily occur.

In pointing out the utility of overestimation for promoting heightened sensitivity to small differences in small slants, I am not arguing that this utility is the principal cause for the form of the psychophysical function. Changes in such optical variables as texture compression decline with increasing slant (as a cosine function), and thus there are important optical determinants. Still, the magnitude of overestimation is influenced by people's physiological potential to ascend hills, as I discuss later, and this modulation is causally related to its utilitarian value.

Explicit Awareness Informs Action Planning

In the case of locomotion, explicit awareness promotes the efficient selection of long-term action plans, such as where and how fast to walk. The visual guidance of coordinated walking occurs largely outside of awareness, and to this end, the accurate use of visual information is paramount. However, deciding how fast to walk may require some explicit thought. One can decide to run, jog, walk, saunter, and so forth, at will.

Choosing locomotor speed depends on three factors: purpose, anticipated duration, and anticipated energetic costs. With respect to purpose, I may rush to my office because I am late for a meeting, or I may dally because it is a beautiful day outside. The selected rate of locomotion is influenced by the benefits accrued from either hastening or delaying the time of arrival at one's destination. The anticipated speed, duration, and energetic costs of locomotion are integrally related. The faster one walks or runs, the shorter is the time to exhaustion. A fit person can walk at a moderate pace for hours, but most people cannot run for this duration. In general, people can sustain maximum aerobic energy expenditure for about 2 hr, whereas maximum anaerobic activity can be sustained for only 10 to 20 s (Knuttgen, 2003). Individuals vary in their aerobic range of energy expenditure as a function of their physical fitness and current physiological state. Thus, in choosing walking speed, one is also choosing rate of energy expenditure, which in turn determines the duration over which this speed can be sustained. Once speed is selected, more automatic processes that optimize gait are engaged (Hoyt & Taylor, 1981; Hreljac, 1993).

Explicit Awareness Is Influenced by Physiological Potential

Explicit awareness relates the distal inclination of hills to the perceiver's physiological potential to ascend them. Hills appear steeper as a function of both increased slant and increases in the energy anticipated to be required for climbing them. This modulation of apparent slant by energetic considerations serves to promote efficient energy expenditure.

Our first experiment exploring this idea manipulated anticipated effort by inducing fatigue in participants (Proffitt et al., 1995). We recruited people who were regular runners and asked them to schedule their most demanding run of the week to coincide with the time when they would participate in our experiment. Prior to their run, we obtained verbal, visual, and haptic slant judgments for a first hill. The participants then ran for about an hour, arriving at a second hill at which slant judgments were again obtained. The starting and finishing hills were different and were counterbalanced across two groups of participants. The measures of explicit awareness (i.e., verbal and visual judgments) indicated that hills appeared much steeper after the run than prior to the run (see Fig. 7). In this experiment, as in all subsequent studies, the manipulation of physiological state did not influence the visually guided haptic measure of slant.

We next manipulated anticipated effort by having participants wear a heavy backpack while making slant judgments. The verbal and visual assessments, but not the visually guided haptic responses, showed that this encumbrance increased overestimation of slant (Bhalla & Proffitt, 1999). We then looked at physical fitness by recruiting student varsity athletes and other undergraduates with varying fitness levels. All were assessed on a stationary-bicycle test that provided a fitness index related to oxygen uptake and recovery time. These participants then made slant judgments for four hills. The two measures of explicit awareness were negatively correlated with fitness, indicating that the more fit the person, the shallower he or she judged the hills to be; the visually guided measure was not correlated with fitness (Bhalla & Proffitt, 1999). Finally, we assessed elderly people and obtained a self-report assessment of their health. We found that the verbal and visual measures of slant were positively correlated with age and declining health, and that the haptic measure was uncorrelated (Bhalla & Proffitt, 1999).

A consistent finding across all of these studies is that hills appear steeper as physiological potential is reduced. The virtue of this modulation of apparent slant by energetic considerations is that it simplifies explicit locomotor planning. People do not have to explicitly relate the apparent incline of a hill to their current state; the hill's incline and the perceiver's state are coupled in perception. The visually guided action of adjusting

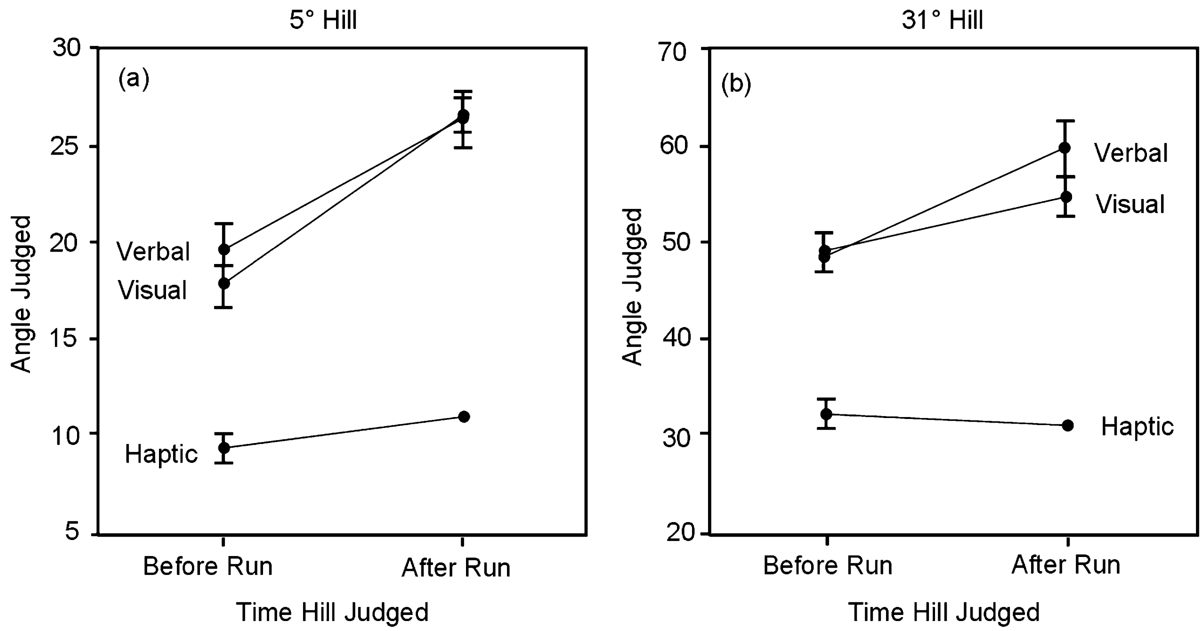

Fig. 7. Mean slant judgments made by runners before and after their runs (from Proffitt, Bhalla, Gossweiler, & Midgett, 1995). Perceived slant was measured verbally, visually, and haptically for a 5° hill (left) and a 31° hill (right). Error bars indicate ±1 *SEM*.

the palmboard was dissociated from the explicit-awareness measures; none of the manipulations that influenced the latter measures influenced the former one. The functional imperatives for visually guided actions require accurate accommodations to the immediate, proximal environment. The planning that occurs in explicit awareness—for example, choosing locomotor speed—needs to weigh the benefits and costs of acting over a larger scale of space and time, and this requires that the environmental opportunities for action be related to their energetic costs.

DISTANCE PERCEPTION IN THE ECONOMY OF ACTION

Unlike geographical slant, which is overestimated, egocentric distance tends to be underestimated when assessed by verbal reports or visual matching tasks (Amorim, Loomis, & Fukusima, 1998; Loomis, Da Silva, Fujita, & Fukusima 1992; Norman, Todd, Perotti, & Tittle, 1996). Another dependent measure, blind-walking, tends to be fairly accurate (Loomis et al., 1992; Rieser, Ashmead, Talor, & Youngquist, 1990; Thomson, 1983). In blind-walking, participants view a target and then attempt to walk to its location while blindfolded.

We have found that manipulating the energetic costs associated with acting on an extent influences apparent distance regardless of the measure used. Although the palmboard adjustment used in studies of visually perceived slant was found to be immune to the influence of energetic manipulations, no visuomotor measure of egocentric distance has been found to be immune to such influence. Some researchers have suggested that blind-walking is a behavior guided by the visuomotor system; however, Philbeck and Loomis (1997) have shown that manipulations that affect explicit judgments of distance, such as verbal reports, also influence blind-walking. In addition, Witt and I showed that blind-walking is influenced by the energetic costs associated with walking (Witt & Proffitt, 2005a). It should be noted that these studies assessed perceived egocentric distances of many meters, whereas visually guided actions are thought to be directed at the immediate environment, which extends only to arm's reach or slightly beyond.

My coworkers and I began experimentation on perceived distance by employing the backpack manipulation that we had used previously in our studies on perceived hill slant. Participants stood in an open field and verbally judged the distances to targets. Those who wore a heavy backpack judged the distances to be greater than those who did not (Proffitt, Stefanucci, Banton, & Epstein, 2003). In another study, participants threw either a heavy or a light ball at targets and then made verbal distance judgments. Those who threw the heavy ball judged target distances to be greater than those who threw the light one (Witt, Proffitt, & Epstein, 2004). We replicated this latter finding using a visual matching task in which participants matched an extent in the frontal-parallel plane to the egocentric extent (Witt et al., 2004).

A very reasonable objection would be that these manipulations might have created a response bias, so that the results might not reflect an influence on perception itself. After all, if people are asked to wear a heavy backpack while making distance judgments, they might well suspect that the backpack is supposed to have an effect on their judgments—why else are they being asked to wear one? To reduce the plausibility of this objection, we ran a study in which a visuomotor adaptation was manipulated. In this study, the connection between the manipulation and distance perception could not have been intuited by participants, and thus, the results could not have been tainted by their expectations. (In fact, the influence of this adaptation on perception was not predicted by us either; we discovered it quite by accident while conducting a study designed for other purposes.)

Whenever people walk or run on a treadmill, they acquire a visuomotor adaptation due to the pairing of forward locomotion effort with an absence of optic flow. Upon stopping and getting off a treadmill, people report that the world seems to be moving by too quickly (Pelah & Barlow, 1996). Another way to demonstrate this aftereffect is to have people walk on a treadmill and then attempt to march in place on the ground while blindfolded. Believing that they are remaining in place, they will actually march forward about 1 to 1.5 m in 15 s (Anstis, 1995; Durgin et al., 2005). The reason for this is that, during adaptation, the visuomotor system recalibrates to the experience of forward walking effort being required to remain in place. Given that effort is required to go nowhere, it follows that after treadmill adaptation, more effort will be required to walk a prescribed distance.

We manipulated anticipated walking effort by having people walk on a treadmill at 3 mph for 2 min (Proffitt et al., 2003). Before this adaptation, participants made verbal judgments of distances to targets. During the treadmill-walking phase, half of the participants experienced appropriate 3-mph optic flow, whereas the other half experienced 0-mph optic flow. The manipulation of optic flow was achieved by having participants view a moving or stationary virtual world in an HMD. Following adaptation, participants judged the distance to a target that was 8 m away. The proportional change in estimates of this target distance from pre- to posttest is shown in Figure 8. As predicted, for the participants who experienced 0-mph optic flow during treadmill adaptation, the target appeared farther way at the posttest than at the pretest. For the participants in the canonical optic-flow group, apparent distance decreased after adaptation—a result that was not anticipated and takes a bit of explaining.

As does any aerobic activity, walking on a treadmill produces a warm-up effect in which cardiovascular efficiency is improved (Bergh & Ekblom, 1979; Chwalbinska-Moneta & Hanninen, 1989). Thus, after a warm-up, less energy is required to walk a prescribed distance. This decrease in anticipated energy expenditure accounts for the reduction in apparent distance following treadmill adaptation with appropriate optic flow. We tested this account by having people warm up on a stationary bicycle. As predicted, this manipulation also evoked a decrease in apparent distance (Riener, 2005).

In the original treadmill study, both groups walked on the treadmill and benefited from warming up. The groups differed only in whether or not they experienced appropriate optic flow, so the approximately 18% difference in the estimates of the two groups (Fig. 8) reflects the magnitude of the visuomotor adaptation. Thus, eliminating optic flow increased distance judgments by about 18%. This is a big effect.

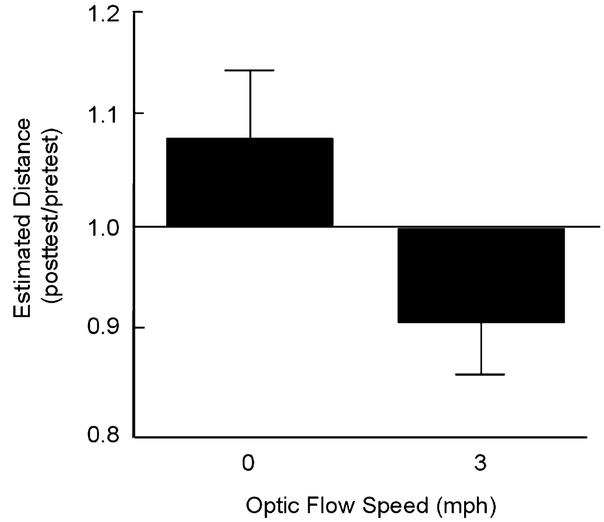

Fig. 8. Proportional change in apparent distance due to treadmill walking with or without optic flow (from Proffitt, Stefanucci, Banton, & Epstein, 2003). Error bars indicate ±1 *SEM*.

INTENTION, EFFORT, AND DISTANCE PERCEPTION

Given that perception relates distal layout to the energetic costs of acting, it ought to be the case that effort's influence on perception is conditional on the particular actions that people intend to perform. For example, if after walking on a treadmill (0-mph optic flow), a person views a target with the intention of throwing a beanbag to it, then apparent distance ought not to be affected because the treadmill adaptation changes anticipated walking effort, but not anticipated throwing effort. This is exactly what we have found.

In a set of studies, we varied both the function that was adapted—walking or throwing—and the action that participants anticipated performing after making a distance judgment—again, either walking or throwing (Witt et al., 2004). In the first study, people adapted to walking on a treadmill with 0-mph optic flow. Prior to adaptation, they made verbal judgments of the distances to targets. During this pretest, we introduced an intention manipulation: One group of participants threw a beanbag at each target immediately after judging the distance to it, whereas the other group blind-walked to the location of each target after judging the distance to it. The purpose of this manipulation—having participants either throw or walk following their distance judgments—was to create the expectation that during the posttest they would do the same thing. Following treadmill adaptation, the participants viewed a target and made a distance judgment with the expectation that they would next either throw a beanbag or blind-walk to its location. As is shown in Figure 9, the participants who anticipated walking to the target were affected by the treadmill adaptation in a way that caused their distance judgments to increase. This finding replicated that of our previous study; walking on a treadmill while experiencing 0-mph optic flow induced an increase in the anticipated effort associated with walking and increased apparent distance accordingly (Proffitt et al., 2003). In contrast, participants who experienced the identical pairing of 0-mph optic flow and treadmill walking but who anticipated that they would throw a beanbag at the target were influenced only by the warm-up effect, and therefore judged the target to be closer at posttest than at pretest. Changing the anticipated effort associated with walking to a target influenced its apparent distance when participants anticipated walking to, but not throwing to, its location.

In another experiment, we used a similar manipulation of intention, but this time throwing a heavy ball, rather than treadmill walking, was the adaptation (Witt et al., 2004). As in one of our previous studies, participants threw a heavy ball to targets and then made verbal distance judgments. In this experiment, however, there were two groups defined by what action was performed immediately after each verbal judgment. One group threw the heavy ball to the target a second time, whereas the other group blind-walked to the target's location. The group that threw the ball again judged distances to be greater than the group that blind-walked to the target following the distance judgments.

In both of these experiments, participants made distance judgments from the action perspective of being either a "thrower" or a "walker." If they were a thrower, then they were influenced by the effort required to throw but not to walk. If they were a walker, then effort for walking, but not for throwing, affected apparent distance. The apparent distance of a target is a function of both its actual distance and the effort associated with intended actions directed to it.

A final experiment assessed whether these effects were, in fact, perceptual or due to influences occurring postperceptually (Witt & Proffitt, 2005a). Participants were assigned to one of two groups. Those in the first group were told that they would walk on a treadmill and then blind-walk to a target. Those in the second group were told that they would walk on a treadmill and then throw a beanbag at a target while blindfolded. Both groups walked on the treadmill with 0-mph optic flow and then observed the target, with participants in one group believing that they would next blind-walk to the target and those in the other group believing that they would next throw a beanbag to it. All participants were then blindfolded, making no distance judgments prior to donning the blindfold. The group that anticipated blind-walking to the target did so, and as Figure 10 shows, they overshot its location. The group that expected to throw was given an unanticipated change in instructions after they donned the blindfold. They were told that a mistake had been made in the prior instructions and that, in fact, we wanted them to walk blindfolded to the target location. These participants undershot the target location (see Fig. 10). This experiment shows that perception is influenced by the action that is anticipated during viewing of the target. Participants who viewed the target as

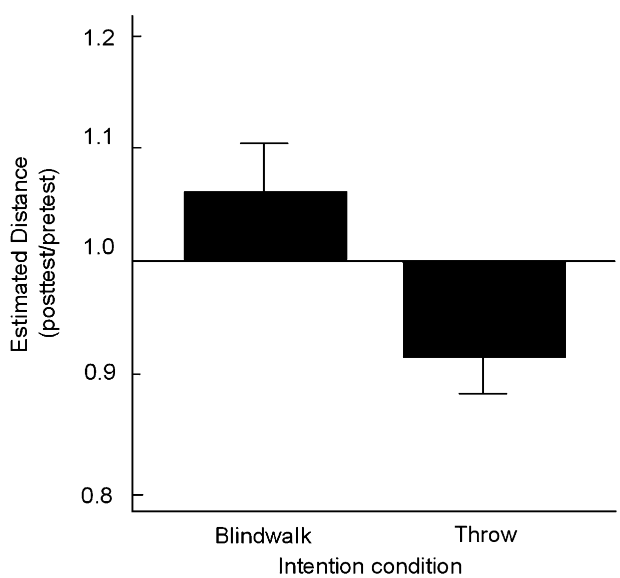

Fig. 9. Proportional change in apparent distance due to treadmill walking without optic flow (from Witt, Proffitt, & Epstein, 2004; reprinted with permission from Pion Limited, London). One group made judgments with the anticipation that they would blind-walk to the target, whereas the other group anticipated throwing a beanbag to its location. Error bars indicate ±1 *SEM*.

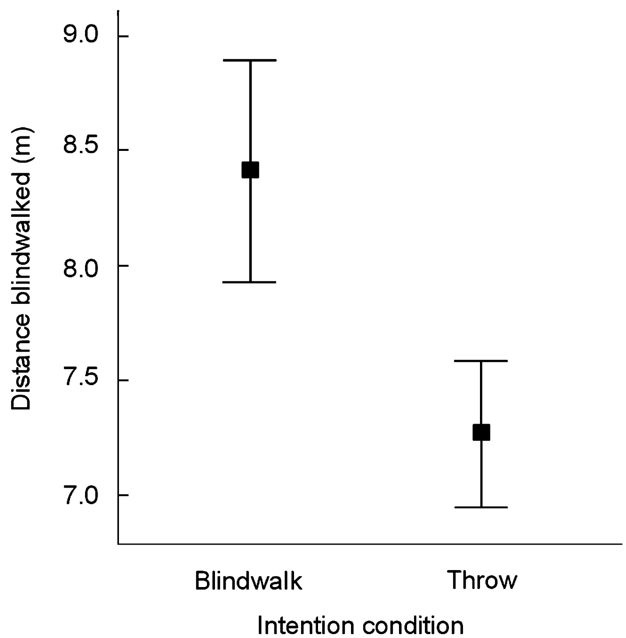

Fig. 10. Mean distances blind-walked to a target that was 8 m away (from Witt & Proffitt, 2005a). One group viewed the target with the expectation of throwing to its location blindfolded; however, after donning the blindfold, they were instructed to walk to the target. The other group viewed the target with the expectation of subsequently blind-walking to it, and after donning the blindfold, they did so. Error bars indicate ±1 *SEM*.

walkers perceived its distance to be further away than did participants who viewed the target as throwers because the treadmill adaptation increased the anticipated effort associated with walking but not with throwing. Because the throwers were blindfolded before they were instructed to walk to the target, they walked the perceived "throwing distance."

ADDITIONAL COSTS THAT INFLUENCE PERCEPTION

Most of our research to date has focused on energetics' influence on visual perception. Our guiding hypothesis has been that perception makes apparent both the costs and the benefits associated with acting in an environment, and that energy expenditure is a ubiquitous cost of gross bodily movements. There are, of course, other costs, and we have recently begun to investigate the perceptual influence of a few of them. Although this work is still in its preliminary stages, it has produced some intriguing findings.

Some behaviors are physically risky; a person could be hurt as a consequence of performing them. For example, falling is a risk associated with locomotion. For a moderately fit and coordinated person, the risks of falling when walking on level ground are minimal; however, as the ground plane becomes very steep, the cost of falling increases, with falling off a high cliff being catastrophic. We have found that perception is influenced by the possibility and fear of falling in potentially dangerous situations.

In our initial studies of geographical-slant perception, we compared slant assessments made when participants viewed hills from their base looking up with assessments made when participants stood at the top and looked down (Proffitt et al., 1995). For shallow hills, we found no difference; however, for hills that were steeper than about 25°, we found that the explicit-awareness measures—verbal reports and visual matching—were greater when participants viewed from the top. For the grass-covered hills that we used, 25 to 30° was about the limit of what participants could ascend without using their hands, whereas for biomechanical reasons, these hills were too steep to walk down. Attempting to descend a grassy 30° hill would cause most people to fall down or to break into a running gait that would be difficult to maintain or stop. The top of a 30° hill is a dangerous place. That steep hills appear steeper from the top than from the bottom cannot be attributed to energetic costs; in a perverse sense, falling is more energetically efficient than climbing. Rather, we proposed that steep hills look steeper from the top because of the potential injury costs associated with descending them. In essence, we proposed that the apparent incline of steep hills is influenced, in part, by a fear of falling.

Recently, we tested more directly whether fear of falling influences perceived layout (Stefanucci, Proffitt, & Clore, 2005). Two groups of participants viewed, from the top, a paved walkway that descended a 7° hill. (Remember that for us humans, a 7° hill is actually quite steep.) One group stood on a skateboard, whereas the other group stood on a box of equivalent dimensions. As in the previous studies, apparent slant was assessed with two measures of explicit awareness—verbal judgments and visual matching—and the visually guided action measure—the palmboard. In addition, while standing on the skateboard or box, participants completed a rating-scale measure of their fear of descending the walkway. For the explicit-awareness measures, the apparent incline of the hill was greater among participants who stood on the skateboard and reported feeling scared compared with those who stood on the box and reported no fear of falling. (The palmboard adjustments were unaffected by either the skateboard manipulation or individual differences in reported fear.)

In her dissertation research, Stefanucci (2005) is currently investigating the perception of vertical extent when people look down from a height, such as a balcony, as opposed to when they stand on the ground and look up. Using a visual matching task in which participants match a horizontal distance to the vertical extent that they are viewing, she has found huge overestimations of vertical extent when people look down and much smaller overestimations when they look up. Of particular interest, people's assessed anxiety about falling has been found to be positively correlated with apparent distance.

These preliminary studies provide evidence that fear of falling affects both the apparent steepness of hills and the perceived vertical height of a balcony from which one could fall. Falling is a negative consequence of performing certain behaviors in risky environments. Spatial layout and the costs associated with falling are coupled in perception, thereby making the danger more obvious.

We constantly ask ourselves, "What other nonvisual factors might affect visual perception?" In attempting to answer this question, we have looked to the field of behavioral ecology for help.

CURRENCY AND THE ECONOMY OF ACTION

Behavioral ecology examines how animals are suited for the task of balancing the costs and benefits of their behavior in the circumstances that arise within their niche (Krebs & Davies, 1993). A guiding notion is that evolutionary selection pressures favor those individuals that optimize the cost/benefit trade-offs associated with everyday activities, and thereby increase their chances of passing along their genetic material into the future. For bees, relevant everyday activities include foraging for food. In collecting nectar, bees encounter a cost/benefit trade-off between the amount of nectar collected and the energy required to transport this load. Schmid-Hemple, Kacelnik, and Houston (1985) found that bees optimize their energetic efficiency by decreasing load size as foraging time increases. (In other studies that delight us to no end, Schmid-Hemple, 1986, affixed weights to bees—"tiny bee backpacks"—to investigate the influence of transport energy on foraging behavior.)

A key step in developing models in behavioral ecology is finding the *currency* of costs and benefits (Krebs & Davies, 1993). In the case of bee foraging, the cost currency is energy expenditure, and the benefit currency is energy delivered to the hive. Bees optimize efficiency: energy delivered per energy expended over the foraging duration. This optimization is thought to confer on bees an adaptive advantage over use of less optimal strategies or optimal solutions applied to other currencies that are less applicable to their ways of life.

This notion of currency can be applied directly to the energetic costs and benefits that influence human visual perception. Consider again our contention that in perception of surface layout, a function of explicit awareness is to inform decisions about locomotor speed. A cost related to locomotor speed is rate of energy expenditure, which in turn relates to time to exhaustion. In planning efficient locomotion, the intended duration of the excursion is critical. Thus, rate of energy expenditure and locomotion duration are among the currencies that define locomotor costs. Seeing these costs in the world eliminates or reduces the need to explicitly deduce their influence. Explicit action plans can be based on how things appear, so that one does not have to separately take into account each of the relative costs. (A principal function of perception is to defend people from having to think.) Simplified action planning is an adaptive consequence of seeing the world in terms of costs and benefits. People walk more efficiently because they see their current potential to expend energy over time in the layout of their environment.

With respect to fear of falling, the cost currencies are bodily injury or death. Failing to avoid these costs is a sure way to reduce the likelihood of passing one's genes on to the future. The perceptual exaggeration of steep hills and high places increases their apparent threat, and thereby promotes caution and its adaptive advantage.

Returning to the question of what other nonvisual factors are likely to influence perception, a working heuristic is that they ought to be currencies with adaptive value. That is, we think it unlikely that visual perception can be altered by nonvisual influences unless there are adaptive reasons to do so. Our approach has been to look for adaptive currencies, such as energy expenditure, that are critical costs of behaving. We have, however, begun to look at other adaptive variables that are related to the body but not necessarily to the economy of action.

OTHER BODILY INFLUENCES ON SPATIAL PERCEPTION

Affordances

Gibson's (1979) notion of affordances conveys the idea that perception relates surface layout to the action potential of the body. In recent studies, we have shown that when a person's action potential changes, perceived surface layout changes as well (Witt, Proffitt, & Epstein, 2005). On a given trial, participants observed a target dot, which was projected onto the table before them. Using a visual matching task, participants indicated the egocentric distance to the target and then reached out and touched it. If the target was beyond reach, they pointed to its location. In half of the trials, participants touched or pointed to targets with their index finger, whereas in the other trials, they held a conductor's baton and touched or pointed with it. For those targets that were out of finger's reach but could be touched with the baton, target distances appeared nearer when the baton was held. Augmenting the body's reaching potential, through tool use, caused a change in how close targets appeared to be.

In many situations, people may be able to perform an action, but perhaps not as well as they would like. Competitive sports illustrate the ephemeral nature of affordances. In the case of professional baseball, batters fail to hit the ball more often than they succeed. Of particular interest to us, professional baseball players often comment that the apparent size of the ball changes with their ability to hit it. For example, in describing a towering home run, Mickey Mantle once said, "I never really could explain it. I just saw the ball as big as a grapefruit" ("Mickey Mantle," n.d.). We conducted an experiment designed to determine whether such observations are true (Witt & Proffitt, 2005b). Players in a local softball league were approached following their game and asked to indicate the size of a softball and also to report on their hitting performance during their just-completed game. The apparent size of a softball was correlated with batters' recent batting average.

Social Influences

As already described, reachability—which may be influenced by holding a tool—influences apparent distance. Objects that are reachable are perceived to be closer than those that are not. The extent of reachability defines one's personal space (Cutting & Vishton, 1995). This body-scaled space has social significance; people claim ownership of their personal space. A recent study has found that the ownership of specific objects within personal space influences their apparent distance (Schnall et al., 2005). Students at an outdoor café were approached by an experimenter and asked if they would be willing to participate in a short experiment. Those who agreed were assigned to one of two groups. For both groups, a soda can was placed within the participant's personal space. For one group, the can was unopened and had been given to the participant, whereas for the other group, the can was opened and belonged to the experimenter, who had just drunk from it. All participants performed a visual matching task to indicate the egocentric distance to the soda can. Participants whose personal space had been invaded by the experimenter's can viewed the can as being closer than did participants who were assessing the distance to their own can. The locations of the soda cans were the same across groups; each can's apparent distance within personal space was influenced by its ownership.

Emotions

As discussed earlier, we have shown that fear of falling influences apparent slant and vertical extent. For example, people looking down from a high balcony view the extent to the ground as being greater if they are fearful than if they are not fearful. We have also conducted preliminary studies on the influence of mood on apparent slant (Riener, Stefanucci, Proffitt, & Clore, 2003). Participants viewed hills while listening to music through headphones. One group listened to a major-key piece by Mozart, whereas the other listened to a minor-key piece by Mahler (methodology adapted from Niedenthal & Setterlund, 1994). We found that explicit measures of the hill's slant—verbal reports and visual matching—were affected by the mood manipulation, whereas visuomotor adjustment of the palmboard was not. Relative to participants who listened to the "happy" major-key music, those who listened to the "sad" minor-key music viewed the hills as being steeper. It will take considerably more work to determine whether or not mood's influence on spatial layout is mediated by underlying physiological processes associated with energetics.

THEORETICAL PRECURSORS

I know of no other theoretical approach that claims visual perception is modulated by such bodily influences as the energetic costs associated with intended actions. However, the notion that perception is embodied and action oriented is ubiquitous in Gibson's (1979) ecological approach, and his ideas have had the most significant and direct influence on the development of our perspective.

Gibson (1979) proposed that the purpose of perception is to inform and guide actions. For Gibson, perceptual meanings were the behavioral possibilities apparent in the environment relative to the organism's physiology and ways of life. As already noted, he termed these body-scaled utilities affordances. For example, a person might perceive that an object affords grasping, that a surface affords walking, or that a cliff affords falling. Gibson stated, "The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill" (p. 127). I view the current approach as being a development of this idea, and I am deeply indebted to it.

Our research showing that perception is mutable to such influences as energetics could be viewed as either consistent or inconsistent with Gibson's approach, depending on one's interpretation of what Gibson wrote. (Countless debates with proponents and opponents of Gibson's theory have made me wary of the contentious consequences of taking a hard stand on this issue.) His writings do not discuss whether energetic costs might influence perception, and I will not presume to guess what Gibson might have said had our findings emerged in time for him to comment on them.

Warren (1983) introduced the notion of energetics into the definition of affordances by observing that animals optimize their energy expenditure in ways that must be supported by perception. In a set of elegant studies, he demonstrated that when people were shown stairs of varying riser heights and asked which they would prefer to climb, they preferred heights that would promote minimum energy expenditure (Warren, 1984). These studies showed that people's judgments about perceived surface layout are influenced by the energetic costs of action; their preference for the dimensions of stairs revealed sensitivity to the energy associated with ascending them. These findings indicate that people are sensitive to energetics considerations, but not that the apparent metric properties of spatial layout are modulated by the energetic costs associated with action.

The susceptibility of perception to nonvisual influences was advocated by Bruner, who with his colleagues developed a position called the New Look in perception. The "New Lookers" wanted to show that perception is influenced by such psychological variables as value, need, and social concerns. In an influential set of studies, Bruner and Goodman (1947) found that the perceived size of coins was biased by their worth and—here is the really startling finding—that poor children overestimated the size of valuable coins more than wealthier children did. These blockbuster findings did not withstand critical scrutiny, and the studies were found to be fraught with methodological and interpretive flaws (Carter & Schooler, 1949; Pastore, 1949; Tajfel, 1957). Today, these findings are viewed as being discredited (Gordon, 2004).

What most distinguishes our work from that of Gibson or Warren is our findings that perception is mutable to nonvisual influences. Under conditions of constant visual stimulation, the apparent dimensions of surface layout expand and contract with changes in the energetic costs associated with intended actions. Although unanticipated by Gibson, these findings are grounded in his perspective.

The New Lookers did propose that visual perception is susceptible to nonvisual influences; however, I think that they picked the wrong variables at which to look. Being biased to see valuable coins as bigger than less valuable ones confers no obvious adaptive advantage. In fairness, however, deciding what nonvisual factors are likely to influence perception is far from being a well-defined problem.

CONCLUSION

Everyday experience suggests that the perceptual world reflects the constant geometric properties of the environment. That is, people assume that their perceptions are accurate and reliable representations of the world around them. It has been shown, however, that visual perception is malleable, and that people perceive the geometry of spatial layout in relation to an ever-changing potential to act on the environment and the costs associated with these actions.

Under constant viewing conditions, hills appear steeper when people are tired or encumbered by wearing a heavy backpack; hills also appear steeper to people who are in poor physical condition or who are elderly and in declining health than to people who are in better condition. Similarly, distances appear greater when people are encumbered by a backpack, are throwing a heavy ball, or have just gotten off a treadmill. When one is standing on a high balcony, the distance to the ground is related to one's fear of falling.

In a pragmatic sense, these distortions of the environment's apparent geometry provide useful representations of its layout. Not only are the possibilities for acting apparent, but so too are the costs of these actions. The visually specified layout of the environment is modulated in perception in ways that promote effective, efficient, and safe behavior. Perception scales the geometry of spatial layout to the economy of action.

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