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# Visual Guidance of Walking Through Apertures: Body-Scaled Information for Affordances

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A necessary condition for visually guided action is that an organism perceive what actions are afforded by a given environmental situation. Warren (1984) proposed that an affordance such as the climbability of a stairway is determined by the fit between properties of the environment and the organism and can be characterized by *optimal points,* where action is most comfortable or efficient, and *critical points,* where a phase transition to a new action occurs. Perceiving an affordance, then, implies perceiving the relation between the environment and the observer's own action system. The present study is an extension of this analysis to the visual guidance of walking through apertures. We videotaped large and small subjects walking through apertures of different widths to determine empirically the critical aperture-to-shoulder-width ratio ($A/S$) marking the transition from frontal walking to body rotation. These results were compared with perceptual judgments of "passability" under static and moving viewing conditions. Finally, we tested the hypothesis that such judgments are based on intrinsic or body-scaled information specifying aperture width as a ratio of the observer's eyeheight. We conclude (a) that the critical point in free walking occurs at $A/S = 1.30$, (b) that static monocular information is sufficient for judging passability, and (c) that the perception of passability under such conditions is based on body-scaled eyeheight information.

A necessary condition for the visual guidance of action in complex environments is that the organism perceive what actions are afforded by a given situation. In this article, we examine the affordance problem for the case of visually controlling body rotation when walking through narrow apertures. Our goals are to provide a precise description of the material relations that constrain an action, to characterize the available optical information that specifies these relations, and to determine whether humans are sensitive to such information. This is preliminary to an account of the process by which the information is detected and used to regulate motor parameters (Warren, in press; Warren, Young, & Lee, 1986). Given that organisms exploit these material and informational constraints in the perceptual control of action, we believe that the problem of the organization of behavior will be greatly simplified by developing such a theory of constraints (cf. Gould & Lewontin, 1979). Specifically, perception and action categories and preferences may be shown to have a natural basis in the constraints of the organism–environment system.

## Analyzing Affordances

The *affordances* of an environmental object or situation, as described by Gibson (1979), are the activities that it offers or affords for an organism with certain action capabilities (see also Turvey & Shaw, 1979). Such functional possibilities for action are determined by the fit between properties of the environment and properties of the organism's action system. For example, an object affords grasping if its size, shape, and surface composition are compatible with the functional morphology of the organism's prehensile limb (Newell & Scully, 1987), and an aperture affords passage if its width is greater than the organism's narrowest horizontal dimension. A general theory of affordances is thus a theory about the behavior of an ecosystem rather than of an individual and requires an explication of both (a) the material basis for an affordance in the relation between organism and environment and (b) the informational basis for perceiving an affordance in the optical patterns that specify that relation.

In an earlier article, Warren (1984) proposed an analysis of affordances that utilized methods of intrinsic measurement and dimensional analysis to describe an organism–environment system. These methods scale relevant environmental variables to action system variables, yielding dimensionless body-scaled ratios known as pi numbers that characterize a particular organism–environment fit (Schuring, 1977; for an introduction, see McMahon & Bonner, 1983). As the fit is varied, *optimal points* in the ecosystem may emerge for preferred states at which a given action is most comfortable or efficient, and *critical points* will emerge at which the limits on an action are reached and a phase transition to a qualitatively different action occurs. For example, as the diameter $D$ of an object increases relative to the span of the hand $H$, an optimal region occurs over which a one-handed power grip is most effective, and ultimately a critical point will be reached at which a one-handed grip gives way to a two-handed grip, requiring a reorganization of the musculature. Particular values of the dimensionless pi number

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$\pi = D/H$ correspond to these optimal and critical points. Although this simple example involves only geometric variables, other affordances may involve kinematic (spatiotemporal) or dynamic (force and mass related) variables as well. Because pi numbers capture intrinsic relations, their critical and optimal values are scale independent for physically similar systems (Rosen, 1978); that is, the optimal and critical ratios should be constant regardless of the absolute size of the actor. In sum, such ecological constraints determine what a given situation affords for action, and the optimal and critical points of an affordance emerge out of the dynamics of the ecosystem.

Given this description of affordances, how might an organism exploit them for the guidance of action? First, the affordances of an object could be determined by an actor on the basis of *extrinsic information*, which specifies the absolute dimensions of the environment in terms of some arbitrary metric. On this account, once an objective spatiotemporal representation of the environment is obtained, it could be compared with knowledge about the organism's body dimensions or motor abilities, and possible courses of action could be computed or inferred. This process would require a translation from an absolute coordinate system into the body-referenced coordinates and parameters of the action system (see Fitch & Turvey, 1978). Alternatively, if the organism could perceive the relation that holds between properties of the environment and its own action system, as Gibson (1979) proposed, this would provide a principled basis for the direct perception of affordances rather than absolute environmental properties. Affordances could be perceived on the basis of *intrinsic information*, which specifies environmental dimensions relative to the dimensions of the observer in units of some body-scaled or, more generally, action-scaled metric (Warren, 1984). Intrinsic information has the advantage that it is directly relevant to the guidance of action without recoding or comparison with knowledge about the action system. The existence of body-scaled information has been demonstrated for geometric dimensions such as size and distance specified as a ratio of eyeheight (Gibson, 1979; Purdy, 1958; Sedgwick, 1980a; Warren, 1983) or as a ratio of amount of ground texture covered by body segments (a variant on Gibson, 1950; 1959); other action-scaled variables are similarly analyzable (e.g., Lee, 1980; Warren & Kelso, 1985). Thus, on this view the world to be perceived is not a seamless fabric of continuous dimensions, but rather is punctuated by qualitative regions of functional significance to the organism, known as action categories (Shaw & Cutting, 1980; Michaels, Prindle, & Turvey, 1985). Their critical and optimal points are condensed out of continuous variation in the organism–environment fit and are perceptually specified rather than cognitively attributed. These considerations are obviously relevant not only to understanding biological systems but also to the design and control of mobile robots.

Evidence for body-scaled perception was obtained by Hallford (1984) in visual size judgment tasks using a body-referenced standard and an arbitrary standard. Observers were more accurate and had higher confidence when judging whether they could grasp rectangular objects with one hand than when judging their widths relative to a standard object that was first viewed and then held during the judgments. This result indicates the primacy of body-scaled perception. In an independent study of perception and action in stair climbing (Warren, 1984), we also found that perceivers were highly accurate at judging the dimensions of environmental objects with respect to their own action capabilities. Visual judgments of critical riser height by short and tall observers closely corresponded to the critical values predicted by a biomechanical model, and visual judgments of optimal riser height corresponded to the optimal values determined from measurements of energy expenditure during climbing. Further, when these values were intrinsically scaled as ratios of leg length, the resulting critical and optimal pi numbers were constant across short and tall subjects. Thus, our observers appeared to make accurate perceptual judgments of the affordance of "climability" that were scaled to their own body dimensions. Similar results have been found for visual judgments of optimal and maximal sitting height (Mark & Vogele, in press) and maximal reaching distance (Carello, 1985). Research by Ulrich, Thelen, and Niles (1986) indicates that infants just learning to climb stairs can distinguish between climbable and unclimbable stairways. Also, Gibson, Riccio, Rosenberg, Schmuckler, Stoffregen, and Taormina (in press) have found that infants perceive the traversability of surfaces differentially depending on their own action capabilities of crawling or walking.

## Walking Through Apertures

The present study extends Warren's (1984) analysis of critical points to a new affordance—the passability of an aperture during visually guided walking—and investigates the optical information specifying passability. Apertures are ubiquitous in natural cluttered environments, whether they take the form of interstices between objects, doorway-like openings, or extended passageways such as corridors, and they present a common navigational problem for locomotion. With aperture widths that are narrower than the organism's widest frontal dimension—shoulder width in humans—the actor must rotate his or her body to pass, allowing a certain safety margin for body sway and error. Apertures that are narrower than the smallest horizontal body dimension do not afford passage, in which case the organism must locate an alternate path in advance of colliding with the barrier. Perceiving the affordance of passability thus determines what actions are possible with respect to the aperture: (a) maintain a frontal walking gait, (b) reorganize the musculature to rotate the body while passing through the aperture, or (c) detour around it. The present experiment focuses on the critical transition point between (a) and (b), denoted $\pi_{max}$; the critical point between (b) and (c), denoted $\pi_{min}$, is a generalization of the same principles.

We can formalize this simply as follows. As aperture width $A$ decreases toward shoulder width $S$, a phase transition in behavior occurs from a frontal gait to a shoulder rotation. This relation is described intrinsically by expressing aperture width as a ratio of shoulder width, yielding a critical point $\pi_{max}$ at some value greater than 1, allowing for a safety margin:

$$\pi_{max} = A/S > 1. \tag{1}$$

Because this is an intrinsic relation, the critical point should be a constant across actors of different absolute size for physically similar systems. In Experiment 1 we tested this similarity hypothesis and established an empirical value for $\pi_{max}$ in a visually guided task, by examining small and large actors as they walked through apertures of different widths.

## Experiment 1: Critical Aperture Width

In Experiment 1, we empirically determined critical aperture width during visually guided free walking for two groups of male subjects, one with narrow shoulders and one with broad shoulders. Subjects were videotaped while walking through apertures of different widths at two speeds, and shoulder rotation was measured.

### *Method*

#### *Subjects*

Ten male undergraduates were selected for the experiment on the basis of standing height, so that the 5 members of the *small* group were 168 cm or shorter, and the 5 members of the *large* group were 202 cm or taller. Shoulder width, the widest frontal body dimension, was measured from the tip of the left humerus to the tip of the right humerus with the shoulders relaxed, yielding a mean of 40.4 cm for the *small* group (2.5th male population percentile; $SD$ = 2.0 cm) and 48.4 cm for the *large* group (95th percentile; $SD$ = 0.7 cm) (population percentiles from Diffrient, Tilley, & Bardagjy, 1974). Mean standing eyeheight was 157.4 cm ($SD$ = 1.7 cm) for the *small* group and 190.9 cm ($SD$ = 7.6 cm) for the *large* group. The subjects were paid for their participation.

#### *Materials*

A doorway-like aperture was formed between two movable partitions in a 10-m × 15-m gymnasium with a wooden floor and white brick walls. Each partition was a 1.2-m (horizontal) × 2.4-m (vertical) piece of unpainted plywood mounted on end on a triangular base and supported by casters. A 2.4-m (horizontal) × 3.3-m (vertical) tan curtain was hung from the ceiling on either side of the partitions, covering their outer edges, to create the effect of a wide wall with an opening in it. The width of the opening was varied by adjusting the partitions, while the curtains remained fixed. The partitions were oriented perpendicular to the floorboards, which ran straight from the aperture to the subject's feet. The back wall was 4.25 m behind the partitions and was visible through the aperture; it was covered with a seamless black paper backdrop in order to eliminate background surface texture.

A top view of the subject's shoulders during each pass through the aperture was provided by an RCA video camera mounted on the ceiling directly above the aperture, 3.3 m above the floor. It was connected to an RCA VHS videotape recorder with a 30-Hz sampling rate. The edges of the partitions were marked with black tape at heights of 140 and 160 cm above the floor, approximately shoulder height for the two groups of subjects, and the rostral sides of the subject's shoulders were marked with tape at the head of the humerus to facilitate analysis of shoulder rotation.

#### *Procedure*

Each subject was run individually in two speed conditions, presented in the following order. In the *normal-speed* condition, subjects were asked to walk naturally, at a comfortable pace, through apertures of different widths, turning their shoulders if they wished. In the *fast-speed* condition, the task was the same except that they were asked to walk at a fast pace.

On a given trial, the subject began at a starting mark 7 m in front of the aperture, walked through the aperture and around the partitions, and returned to the starting mark. While the subject's back was turned, the experimenter then manually changed the aperture width by lining up the partitions with measured marks on the floor. Aperture width varied between 35 and 90 cm in 5-cm increments. Three sets of trials were run in each speed condition, with a set consisting of one increasing and one decreasing series of trials. An increasing series began with a randomly selected aperture width of 35, 40, or 45 cm and continued in 5-cm steps to the 90-cm endpoint. Conversely, a decreasing series began with a randomly selected width of 90, 85, or 80 cm and continued to the 35-cm endpoint. Thus, an experimental session consisted of approximately 132 trials and lasted about an hour. Only data from the 40-cm to 85-cm apertures were analyzed further. The two values of shoulder rotation from each ascending-descending series pair were averaged together, yielding three separate estimates of shoulder rotation at each of the central aperture widths. After the last trial was completed, the subject's standing height, standing eyeheight, and shoulder width were measured with an anthropometer.

Shoulder rotation in each trial was determined from the videotapes by measuring the angle between the frontal plane of the shoulders and the plane of the partitions at the moment the center of the subject's head reached the shoulder-high mark on the partition. A subject's critical aperture width was the mean width at which that subject began to rotate his shoulders above a baseline level of rotational body sway. This was determined by plotting the subject's mean angle of rotation against aperture width and by taking the aperture width immediately preceding the curve's asymptote to be that subject's critical value. Group means for critical aperture width were then calculated from individual subject boundaries.

To determine the subject's approach speed on each trial, we measured the number of video frames between the point at which the center of the subject's head passed the 1 m mark on the floor and the mark on the partition. Approach speed was calculated geometrically from this data, the subject's height, and the camera height.

### *Results and Discussion*

The mean absolute angle of shoulder rotation is plotted as a function of aperture width for each group at the normal speed in Figure 1a and at the fast speed Figure 2a. The curves for the two groups have similar shapes, but the *large* group curve is shifted to the right of the *small* group curve in both speed conditions. The functions appear to decrease linearly at first and then reach an asymptote at some baseline level of rotational body sway at the wider apertures. An analysis of variance (Group × Aperture × Speed) was performed on the subject means for shoulder rotation. This revealed a main effect of aperture width, $F(9, 72) = 151.08$, $p < .001$, as suggested by the steep slopes of the curves, and a group effect, $F(1, 8) = 26.54$, $p < .001$, indicating that *large* subjects had greater angles of shoulder rotation overall than *small* subjects, as suggested by the shift in the group curves. There was also a main effect of speed, $F(1, 8) = 6.31$, $p < .05$, implying that shoulder rotation as greater at the fast speed than the normal speed. It appears from the graphs that this is mainly due to increased rotation by the *large* group at the fast speed. However, the Group × Speed interaction was not significant, $F(1, 8) = 3.58$, *ns,* indicating that the relation between the *small* and *large* groups in the fast condition is not statistically different from that in the normal condition. There was no Aperture × Speed interaction nor a three-way interaction.

To examine the similarity hypothesis that critical points are constant across physically similar systems, the same shoulder

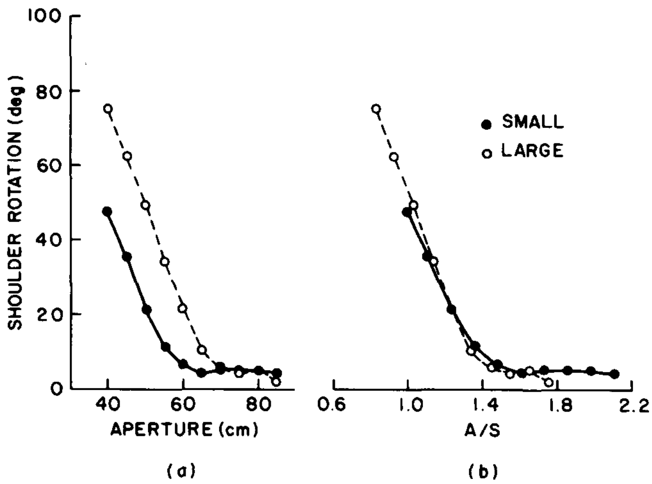


*Figure 1.* Mean absolute angle of shoulder rotation at normal walking speed as a function of aperture width (Panel a) and aperture width normalized for shoulder width ($A/S$) (Panel b) for each group. (Each data point represents the mean of approximately 30 trials.)

rotation data are replotted in Figures 1b and 2b against the dimensionless pi number $A/S$. These two figures are transformations of Figures 1a and 2a, respectively, in which each aperture width has been divided by the mean shoulder width of the corresponding group, thus normalizing for body size. The resulting curves for the two groups are nearly congruent in both the normal and fast conditions. Thus, intrinsic scaling eliminates group differences, indicating that *small* and *large* subjects behave similarly relative to their own body size.

Mean critical aperture widths and their standard deviations, calculated from the mean of three estimates for each subject, appear in Table 1. In the normal-speed condition, the difference between the critical widths for the *small* group (53 cm) and

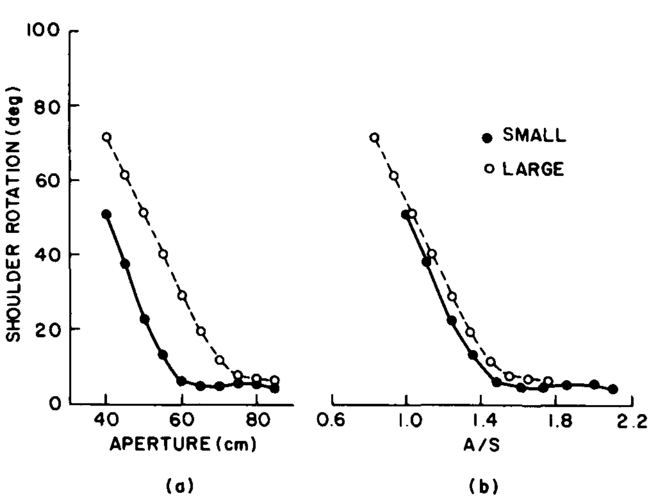


*Figure 2.* Mean absolute angle of shoulder rotation at fast walking speed as a function of aperture width (Panel a) and aperture width normalized for shoulder width ($A/S$) (Panel b). (Each data point represents the mean of approximately 30 trials.)

Table 1
*Means and Standard Deviations of Critical Aperture Widths and Critical A/S Ratios ($\pi_{max}$) for Small and Large Actors at Normal and Fast Walking Speeds*

| | Critical aperture width (cm) | | | | | |
|---|---|---|---|---|---|---|
| | Normal | | Fast | | Critical $A/S$ | |
| Actor | $M$ | $SD$ | $M$ | $SD$ | Normal | Fast |
| Small | 53 | 4.47 | 54 | 4.18 | 1.31 | 1.34 |
| Large | 62 | 4.47 | 66 | 4.18 | 1.28 | 1.36 |

*Note.* $N$ = 5 subjects per group. $A/S$ = aperture-to-shoulder-width ratio.

*large* group (62 cm) was statistically significant, $t(8) = 3.18$, $p < .05$. However, when these values are expressed intrinsically, the $A/S$ ratios are similar: 1.31 for the *small* group and 1.28 for the *large* group, $t(8) = 0.74$, *ns*. Likewise, in the fast speed condition, the difference between critical aperture widths (54 cm for the *small* group and 66 cm for the *large* group) is also significant, $t(8) = 4.54$, $p < .01$, but the $A/S$ ratios are comparable: 1.34 for the *small* group and 1.36 for the *large* group, $t(8) = 0.54$, *ns*. These results lend support to the similarity hypothesis that the critical point is a constant for the ecosystem, regardless of scale changes in the size of the actor. In general, we can conclude that the critical ratio for aperture width at normal speeds is approximately

$$\pi_{max} = A/S = 1.30. \quad (2)$$

Mean speeds of all trials for the *small* group are 1.29 m/s ($SD$ = 0.17) in the normal condition and 1.61 m/s ($SD$ = 0.16) in the fast condition, and for the *large* group are 1.28 m/s ($SD$ = 0.17) in the normal condition and 1.77 m/s ($SD$ = 0.19) in the fast condition. When scaled to shoulder width these increases in speed are comparable for the two groups. The significant effect of speed on shoulder rotation, which is reflected in slightly larger critical aperture widths in the fast condition, could be due to greater lateral oscillations of the upper body or greater caution at high speeds. As noted above, the interaction of speed and group is not significant.

Safety margins were calculated from the data for narrow apertures that induced rotation ($A$ = 40–55 cm for the *small* group, $A$ = 40–65 cm for the *large* group). For the *small* group, mean safety margins are 11.2 cm at the normal speed (5.6 cm at each shoulder) and 11.7 cm at the fast speed; for the *large* group, they are 14.0 cm at the normal speed and 15.5 cm at the fast speed. When normalized for shoulder width, the intrinsic safety margins are .28, .29, .29, and .32 of shoulder width, respectively. This points out the precision of this visually guided whole-body action, with safety margins of only 6–8 cm between each shoulder and the partition at high speeds of travel.

In sum, Experiment 1 empirically establishes the critical point between apertures that are passable and impassable without shoulder rotation to be approximately 1.30 times shoulder width in free walking. This result can now be used to evaluate perceptual judgments of passability under various visual conditions, in an effort to determine the type of optical information observers use to perceive the passability of apertures.

## Experiment 2: Visual Perception of Critical Aperture Width

The previous experiment determined the critical $A/S$ ratio by observing natural visually guided behavior. To examine the optical information that observers can utilize to perceive passability, we asked subjects in Experiments 2 and 3 to judge the passability of apertures from a distance, so that the viewing conditions could be manipulated. If observers can perceive the affordance under these conditions, the visual category boundaries should be close to the critical points found in Experiment 1.

Accurate judgments of passability require that observers have access to either *extrinsic* information about the absolute size of the aperture or *intrinsic* information about the size of the aperture relative to their own body dimensions. Either type of information may be *static,* with a fixed point of observation, or *kinematic,* with a moving observer. Classically, judgments of absolute size have been thought to depend on the visual angle subtended by the target and its perceived absolute distance. However, absolute size and distance judgments based on the isolated cues of accommodation, binocular convergence, and motion parallax have been found to substantially underestimate the range of actual target values, and binocular disparity provides information only about relative depth, not absolute distance; further, the static cues of accommodation and convergence have been found to make a contribution only at distances less than about 1 m (Foley, 1978; Gogel & Tietz, 1973; Leibowitz, Shiina, & Hennessy, 1972). Intrinsic information for size available under richer viewing conditions could provide a natural metric that scales the size of objects to the size of the observer, for example, as a ratio of eyeheight. The static eyeheight ratio is described in detail in Experiment 3. Kinematic eyeheight information is also generated when the observer moves relative to a stable environment, for the focus of expansion of the optical flow field occurs at eye level on the surrounding surfaces (Gibson, 1950; Lee, 1980). Such intrinsic information is available at distances greater than 1 m, but its utilization has not been empirically tested.

Experiment 2 was a first step in determining what optical information is sufficient and what information unnecessary for the perception of passable apertures in a complex scene, comparing perceptual judgments of passability under static monocular and moving binocular conditions. The static viewing condition eliminated kinematic information and rendered accommodation and convergence ineffective by presenting apertures monocularly at distances of 5 m. Thus, accurate judgments of passability in this condition would support the sufficiency of some other static, perhaps intrinsic, variable. The moving condition tested the contribution of additional binocular and kinematic variables, again rendering convergence and accommodation ineffective by presenting apertures at distances of 5 m. Improved performance in this condition would support the utilization of binocular or motion information.

### *Method*

#### *Subjects*

Twenty male undergraduates who had not participated in Experiment 1 were selected on the basis of standing height, so that the 10 *small* subjects were 170.6 cm or shorter, and the 10 *large* subjects were 196.6 cm or taller. Mean shoulder width was 41.4 cm for the *small* group (5th percentile; $SD$ = 1.9 cm) and 47.7 cm for the *large* group (90th percentile; $SD$ = 3.1 cm). Mean standing eyeheight was 164.4 cm ($SD$ = 8.6 cm) for the *small* group and 187.6 cm ($SD$ = 6.7 cm) for the *large* group. Subjects were paid for their participation.

#### *Materials*

The apparatus was the same as in Experiment 1, with the exception that the video equipment and tape markings were removed. In the *static condition,* subjects stood and viewed the aperture monocularly with the preferred eye, looking through a reduction screen with a 3.8-cm (horizontal) × 5.1-cm (vertical) rectangular hole in it that was placed 5 m from the aperture and adjusted to the subject's standing eyeheight. The reduction screen was constructed so as to restrict head and body movements and present an approximately 90° field of view. Both partitions, part of the curtains, and portions of the floor in front of the aperture were visible through the reduction screen, but the side walls and ceiling were occluded. In the *moving condition,* the reduction screen was removed, and subjects viewed the aperture binocularly while walking in a straight line from a starting mark 7 m in front of the aperture to a stopping mark 5 m in front of it, whereupon they reported their judgment. Head and body movements were otherwise unrestricted. In both conditions, subjects could see the complete layout of the room before testing began and thus might have established the familiar size of the partitions or their fixed distance from the reduction screen, although subjects never came closer to them than 5 m.

#### *Procedure*

Subjects were run individually in both viewing conditions, presented in a counterbalanced order. They were instructed to make a *yes* or *no* judgment on each trial as to whether they could walk straight through the opening without turning their shoulders. Aperture width varied between 35 cm and 90 cm in 5-cm increments with random starting positions, as in Experiment 1. Subjects covered their line of sight while the aperture width was changed.

Five sets of trials were run in each viewing condition, each set consisting of one increasing and one decreasing series of trials. In order to reduce the total number of trials, the method of limits was used to determine the perceptual category boundary (Ganong & Zatorre, 1980), so that a series of trials was terminated when there was a shift in response for two successive trials (either from *no* to two successive *yes*'s in an ascending series, or vice versa). The subject was informed at the beginning of each series whether it would be ascending or descending. The aperture width that received the last *no* judgment in an ascending series (or the first in a descending series) was recorded as the boundary between impassable and passable apertures, analogous to the width at which shoulder rotation increased above baseline levels in Experiment 1. The two boundary values for each ascending–descending series pair were averaged together, thus yielding five separate estimates of the perceptual category boundary for each subject in each condition. Group means were calculated from mean subject boundaries.

### *Results and Discussion*

The mean percentage of "impassable" judgments is plotted as a function of aperture width for each group in the *static* condition in Figure 3a, and in the *moving* condition in Figure 4a. All curves drop from a true ceiling of 100% to a true floor of 0%, but the *large* group curve is shifted to the right of the *small* group curve in both conditions. An analysis of variance (Group × Aperture × Viewing Condition) was performed on

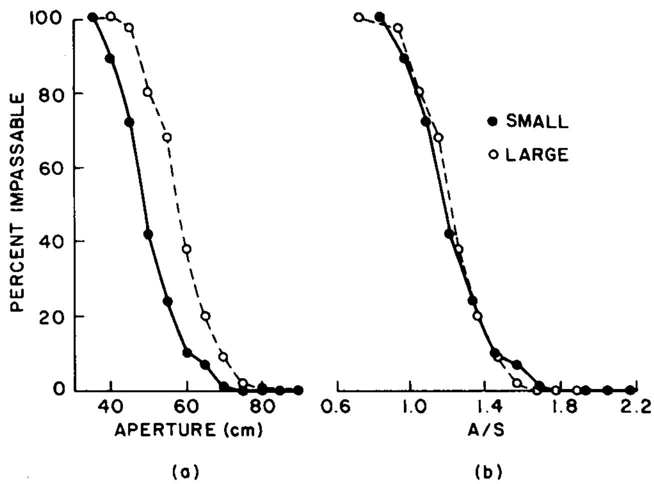


*Figure 3.* Mean percentage of "impassable" judgments in the static viewing condition as a function of aperture width (Panel a) and aperture width normalized for shoulder width ($A/S$) (Panel b). (Each data point represents the mean of approximately 100 trials.)

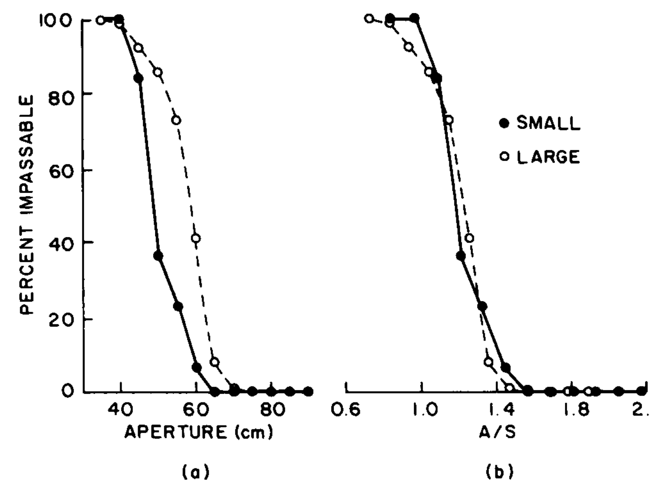


*Figure 4.* Mean percentage of "impassable" judgments in the moving viewing condition as a function of aperture width (Panel a) and aperture width normalized for shoulder width ($A/S$) (Panel b). (Each data point represents the mean of approximately 100 trials.)

the subject means for number of "impassable" judgments. This revealed a main effect of aperture width, $F(11, 198) = 77.10$, $p < .001$, as suggested by the steep slopes of the curves, and a main group effect, $F(1, 18) = 7.68, p < .05$, indicating that *large* subjects gave significantly more "impassable" judgments overall than did *small* subjects. There was, however, no main effect of viewing condition, $F(1, 18) = 0.005$, *ns,* although the Aperture × Viewing Condition interaction was significant, $F(11, 198) = 62.55, p < .001$. In addition, there was a significant Group × Viewing Condition interaction, $F(1, 18) = 6.53$, $p < .01$, a significant Group × Aperture interaction, $F(11, 198) = 5.82, p < .001$, and a significant three-way interaction, $F(11, 198) = 4.86, p < .001$. To examine the similarity hypothesis for the perceptual task, the categorization data are replotted on intrinsic axes in Figures 3b and 4b, thereby normalizing for body size. The resulting group curves are nearly congruent, eliminating the group difference in both viewing conditions.

Mean perceptual category boundaries and their standard deviations, calculated from the mean of five estimates for each subject, appear in Table 2. The *large* group has a larger category boundary than the *small* group in the *static* condition, $t(28) = 2.85, p < .01$, as well as in the *moving* condition, $t(28) = 3.67$, $p < .01$. However, when the boundary values are expressed intrinsically, the critical $A/S$ ratios are similar for both groups in the *static* condition, $t(28) = 0.46$, *ns,* as well as in the *moving* condition, $t(28) = 0.27$, *ns.* Thus, subjects judge the category boundary between passable and impassable apertures to be a constant ratio of their own body size, approximately

$$A/S = 1.16. \tag{3}$$

Although this value is close to that of 1.30 observed in Experiment 1, when subjects actually walked through the apertures, it is statistically different. Assuming that subjects in Experiment 2 based their judgments of passability on normal walking speed, $t$ tests comparing the critical ratio for all subjects in the perceptual task with that in the normal speed action task were significant for both the *static* viewing condition, $t(28) = 2.33, p < .05$, and the *moving* condition, $t(28) = 3.75, p < .01$. Thus, subjects appear to be more conservative about the passability of an aperture when actually walking through it than when judging it from a distance of 5 m. However, we suspect this small difference is due to the wording of instructions in the perceptual task. Experiment 1 was conducted to determine the critical aperture width for natural behavior in freely walking subjects, and, hence, they were instructed to "walk naturally." In Experiment 2, by contrast, subjects were instructed to judge whether they *could* walk straight through the opening without turning their shoulders, rather than whether they *would* do so naturally. Consequently, subjects were biased to judge narrower apertures as passable, and the critical ratio decreased accordingly. Although the results do not offer striking convergence between the two tasks, they do (a) provide strong support for the similarity hypothesis in perception as well as action, (b) indicate that observers can make consistent perceptual judgments of passability at a distance, and (c) provide preliminary evidence for the sufficiency of static information in such judgments.

Table 2
*Means and Standard Deviations of Perceptual Category Boundaries and Critical A/S Ratios for Small and Large Observers in Static and Moving Viewing Conditions*

| | Category boundary (cm) | | | | | |
|---|---|---|---|---|---|---|
| | Static | | Moving | | Critical $A/S$ | |
| Observer | $M$ | $SD$ | $M$ | $SD$ | Static | Moving |
| Small | 47.4 | 8.05 | 47.5 | 5.13 | 1.14 | 1.15 |
| Large | 55.7 | 8.11 | 55.2 | 6.12 | 1.17 | 1.16 |

*Note.* $N$ = 10 subjects per group. $A/S$ = aperture-to-shoulder-width ratio.

Despite the fact that more visual information was available in the *moving* than in the *static* condition, there was no main effect of viewing condition, and the perceptual category boundary values for the two conditions were nearly identical (Table 2). In addition, although the standard deviations of the category boundary are smaller in the *moving* than in the *static* condition for both groups, these differences do not reach significance, $F(9, 9) = 2.45, p < .10$ for the *small* group, and $F(9, 9) = 1.74$, $p < .25$ for the *large* group. Apparently, static monocular information is sufficient for judgments of passability. However, performance in the *static* condition could have been inflated by exposing subjects to the layout of the room prior to testing or by presenting the *moving* condition prior to the *static* condition in half the subjects. But when the standard deviations of category boundary values in the *static* condition are examined for an order effect, there is no statistical difference between those subjects who received the *static* condition first ($SD = 8.08$) and those who received the *moving* condition first ($SD = 10.46$), $F(9, 9) = 1.67, p < .25$. Thus, at least the familiarization with the layout of the room provided by the *moving* condition did not improve performance in the *static* condition. A stronger test is performed in Experiment 3, in which static trials are presented without prior exposure to the apparatus.

Thus, static monocular information appears to be sufficient for consistent judgments of passability, and the addition of kinematic binocular information does not improve performance, indicating that it is unnecessary. Given that extrinsic cues of accommodation, convergence, disparity, and motion parallax do not yield accurate absolute distance judgments, and because it is unlikely that familiar size accounts for the results, static intrinsic information is a leading candidate for the perception of passability. This hypothesis was tested directly in Experiment 3.

## Experiment 3: Eyeheight Information for Passable Apertures

Intrinsic information specifies the relation that holds between dimensions of environmental objects and dimensions of the observer. Given that affordances are defined by precisely such relations, this information offers a potential basis for the direct perception of affordances. Although numerous sources of static intrinsic information for object size may be available, Experiment 3 examined what is perhaps the best understood example, the eyeheight ratio (Sedgwick, 1973; Gibson, 1979).

The architect Le Corbusier (1955) observed, "The eyes are placed at a height above the ground variable according to the size of the person, this being the determining factor of perception" (p. 49). Alberti (1436/1972) discovered the first version of the eyeheight ratio during his experiments with linear perspective, and it is interesting to note that architectural drawings are often drafted from a station point at the eyeheight of the client, so that the objects in the scene appear properly scaled. The eyeheight ratio can be characterized as follows. If an observer standing on an approximately flat ground surface can establish his or her own eye level on other objects that are also resting on that surface, then object height is specified as a ratio of the observer's own standing eyeheight, that is, in units of eyeheight. Intuitively, object height is given as a multiple of that portion of the object that appears below eye level. Formally (Figure 5a), the ratio of object height ($y$) to eyeheight ($e$) is specified by the ratio of the projected height of the object ($y'$) to the portion of projected height that is below eye level ($e'$) (Sedgwick, 1980a). By similar triangles,

$$y/e = y'/e'. \tag{4}$$

This can also be expressed in terms of visual angles as

$$y/e = (\tan\gamma + \tan\theta)/\tan\gamma, \tag{5}$$

where $\gamma$ is the visual angle between eye level and the base of the object, and $\theta$ is the visual angle between eye level and the top of the object. This ratio also holds for objects whose height is lower than eyeheight, in which case $\theta$ is negative. However, it does not generalize to objects suspended above the surface or to ground surfaces that are not approximately flat; in such cases we would expect and often find systematic errors and illusions (e.g., Gibson, 1950, pp. 174–180). If the height of the object is small relative to its distance from the observer, then the visual angles are small and this ratio is approximated by

$$y/e \approx \beta/\gamma, \tag{6}$$

where $\beta$ is the visual angle subtended by the object's total height. Note that we are not suggesting that the observer explicitly perceives eye level and compares it with perceived object size to determine the eyeheight ratio. Rather, we propose that the observer detects optical information that is *already scaled to eyeheight*, such as these ratios of visual angles.

There are two important points to be made here about eyeheight information for size. First, it provides a metric not only for object height ($y$) but also other dimensions of the object perpendicular to the line of sight, such as width ($x$),

$$x/e = [2\tan(\alpha/2)]/\tan\gamma, \tag{7}$$

where $\alpha$ is the visual angle subtended by the width of the object. Thus, the entire scene is scaled to the observer's eyeheight. Second, this information is independent of the distance of the object from the observer, and hence the body-scaled perception of size does not depend on perceived distance. This is so because the ratio of visual angles is constant over changes in the absolute distance to the object (Figure 5a). Sedgwick (1980a) notes that eyeheight information for distance along the ground surface is also available, a reformulation of the classical cue of height in the picture plane,

$$z/e = 1/\tan\gamma, \tag{8}$$

where $z$ is the horizontal distance of the object from the observer. This may provide an informational basis for body-scaled judgments of distance. Nevertheless, eyeheight information for object size remains independent of any form of distance information.

There are a number of sources of information specifying eye level in a static scene. Gibson (1979) and Sedgwick (1973, 1980a) pointed out that in open terrain the visible *explicit* horizon optically intersects any object on the ground surface at eye level (Figure 5b). This is so because for practical purposes the horizon is at an effectively infinite distance from the observer, and hence the line of sight to the horizon is essentially parallel to the ground. Under many conditions, however, the true hori-

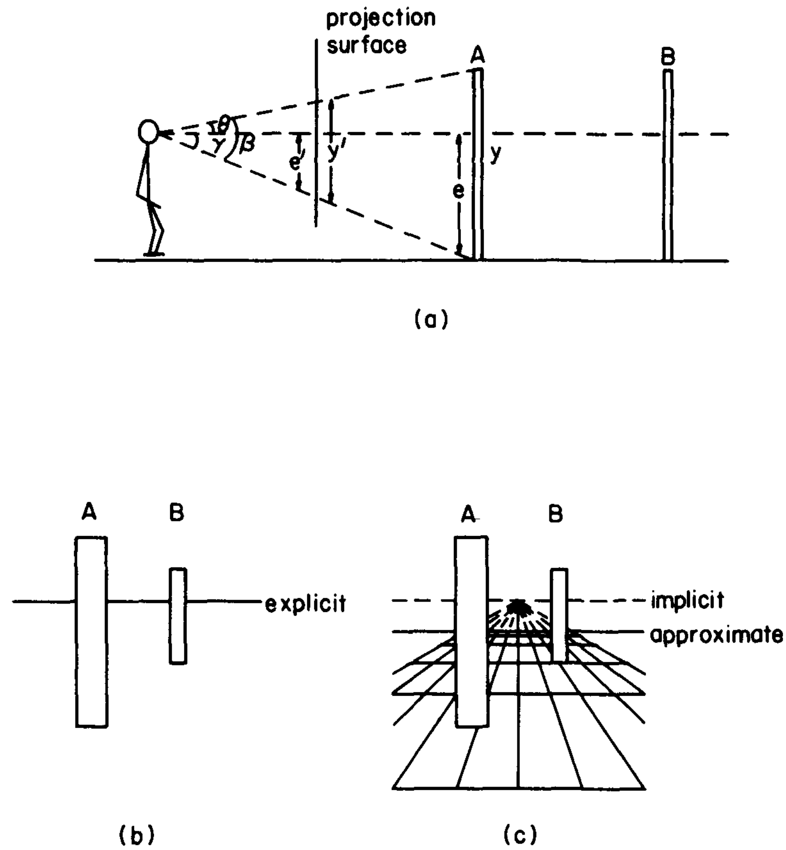


*Figure 5.* Eyeheight information for object size. Panel a: The geometry of the eyeheight ratio for object A (see text). (The ratio is the same for an identical object B at a different distance.) Panel b: The explicit horizon—eye level is given by the height at which the visible true horizon intersects an object. (The heights of A and B are both 1.5 *e*, and their widths are both .25 *e*.) Panel c: The approximate and implicit horizons—the location of the true horizon is given by the limit of optical texture convergence for texture on the ground surface, similar to the height of the vanishing point in linear perspective, and by the limit of optical texture compression.

zon is not visible, such as in an urban environment or indoors. Sedgwick (1980b) has suggested that observers may rely on an *approximate* horizon in such circumstances, that is, the closest visible approximation to the true horizon, such as the base of a building or the corner between a far wall and the floor. However, this would lead to systematic underestimations of eye level and overestimations of object size. A third source of information is available in the optical pattern of ground surface texture. With an approximately flat, horizontal ground surface, the height of the *implicit* horizon lies at the limit of optical texture convergence, similar to the vanishing point of linear perspective, and likewise at the limit of optical texture compression (Figure 5c). Finally, it is possible that vestibular and muscle proprioception about the position of the head and eyes with respect to gravity provides usable information about level gaze. However, Stoper and Cohen (1986) found that judgments of eye level in darkness, when only vestibular and muscle proprioception is available, have a mean constant error that is nearly 10 times greater and a mean variability 66% greater than judgments in the light. Consequently, it appears that eye level under lighted conditions is not simply determined by proprioception.

Thus, intrinsic information specifying the sizes of objects and apertures relative to the observer's eyeheight is in principle available in natural static scenes. Because standing eyeheight ($e$) bears a constant relationship to shoulder width ($S$) in any individual, optical information specifying the ratio $A/e$ also provides information about the ratio $A/S$. For subjects in Experiment 2, shoulder width was on the average .25 of eyeheight, and hence $A/e = 0.25\ A/S$. Thus, judging from the data in Experiment 2, the perceptual category boundary between passable and impassable apertures ($A/S = 1.16$) is specified by a particular margin value of the eyeheight ratio,

$$A/e = 0.29. \tag{9}$$

In Experiment 3 we tested the hypothesis that subjects actually use some form of static eyeheight information by perturbing eyeheight unbeknownst to the observer and by looking for a corresponding shift in the perceptual category boundary. We created a simple Ames room situation in which effective eyeheight ($e^*$) could be reduced 21.5 cm by raising a false floor, thereby decreasing the visual angle $\gamma$ by 4°. The apparatus preserved the impression that the observer was standing on a con-

Table 3
*Means and Standard Deviations (cm) for Observers in the Flat and Raised Conditions*

| | $S$ | | $e$ | | | $e^*_{est}$ | | Category boundary ($A$) | | Eyeheight ratio | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Condition | $M$ | $SD$ | $M$ | $SD$ | $e^*$ | $M$ | $SD$ | $M$ | $SD$ | $A/e$ | $A/e^*$ |
| Flat | 41.4 | 2.9 | 162.1 | 9.0 | 157.6 | 150.7 | 7.37 | 44.3 | 3.5 | 0.273 | 0.281 |
| Raised | 41.2 | 3.4 | 160.7 | 9.5 | 134.7 | 127.5 | 11.0 | 40.0 | 5.9 | 0.248 | 0.296 |

*Note.* $N$ = 15 subjects per condition. $S$ = shoulder width, $e$ = standing eyeheight, $e^*$ = effective eyeheight, $e^*_{est}$ = estimated eyeheight.

tinuous floor, minimizing any cognitive compensation for a known change in eyeheight. To ensure that effective eyeheight was in fact altered, estimates of eye level were obtained in both flat floor and raised floor conditions.

What results would we expect from this manipulation? First, if observers rely on intrinsic eyeheight information, the critical ratio should remain at a constant value of $A/e^* = 0.29$ across conditions. Conversely, based on the eyeheights of subjects in the two conditions in the present experiment, raising the floor should yield a proportional shift of 6.6 cm in the category boundary, so that narrower apertures appear passable. In general, raising the floor should make things look bigger, because their height and width are larger fractions of effective eyeheight, and thus any given aperture should be overestimated with the raised floor. Second, if observers rely on extrinsic information for the absolute size of the aperture and compare it with prior knowledge about shoulder width, the category boundary should *not* shift between conditions, for the relation between absolute aperture size and shoulder width is not altered by raising the floor. Note that although the present experimental conditions eliminated binocular convergence, this cue is known to be ineffective beyond 1 m; it remains a possibility that judgments could be based on some other form of extrinsic information. Third, if observers rely on some other body-scaled information such as a ground texture ratio, we again predicted that the category boundary would not shift, for only the eyeheight relation was altered in the experiment. In sum, we believe the experimental conditions manipulated only intrinsic eyeheight information, thereby testing its effect. However, to control for the possibility that a shift in judgments of aperture width is a consequence of a shift in the perceived absolute distance of the aperture caused by raising the floor, a separate control experiment determined whether absolute distance estimates are also affected by the eyeheight manipulation.

## Method

### Subjects

Thirty new male and female subjects participated in the passability judgment task but were not selected on the basis of body size. Mean height was 172.6 cm (SD = 9.4 cm); other body dimensions appear in Table 3. Another 30 subjects participated in the distance judgment task, with a mean height of 173.1 cm ($SD$ = 9.3 cm), a mean eyeheight of 163.9 cm ($SD$ = 9.2 cm), and a mean shoulder width of 43.3 cm ($SD$ = 2.9 cm).

### Materials

A smaller version of the apparatus used in the previous experiments was constructed in a room 2.4 m wide × 3.9 m deep. Two movable partitions made of foam-core board, each 0.75 m (horizontal) × 2.1 m (vertical), were mounted on end on triangular bases and painted a matte gray. The observer viewed them monocularly through a reduction screen at a distance of 2.2 m, with a seamless black backdrop mounted 0.78 m behind the partitions.

The false floor behind the reduction screen consisted of a platform 1.8 m wide × 2.4 m deep, covered with white contact paper having a gray and brown marbled texture pattern. To create the impression of a continuous floor, the same texture pattern, 1.75 m wide × 1.22 m deep, covered the floor where the observer stood. In the so-called *flat* condition, the platform was placed at its lowest height, 4.5 cm above the floor. In the *raised* condition, the platform was raised to a height of 26.0 cm above the floor, producing a change in effective eyeheight of 21.5 cm. Effective eyeheight ($e^*$) was measured as the distance between the height of the platform and the observer's eye level. Note that the texture pattern provided intrinsic information about aperture width that conflicted with the manipulated eyeheight information: The ratio of the amount of texture filling a given aperture to the amount of texture covered by the observer's stance remained constant across the flat and raised conditions.

The reduction screen had a 1.6-cm (horizontal) × 2.8-cm (vertical) rectangular hole in it, was mounted 24.1 cm in front of a tan curtain with a 15.9-cm (horizontal) × 58.4-cm (vertical) rectangular hole in it, and was adjusted to the subject's standing eyeheight. This arrangement permitted the subject to see only the gray partitions, the black backdrop, the textured floor in front of the partitions, and the bottom edges of the partitions on the floor. The walls and ceiling of the room and the top and outer edges of the partitions were not visible through the reduction screen. The curtain blocked the rest of the apparatus from view throughout the testing session.

### Procedure

*Passability judgments.* Thirty subjects participated in this task, 15 in the *flat* condition and 15 in the *raised* condition. The procedure was identical to that in Experiment 2, except that aperture width varied between 32 cm and 68 cm in 3-cm steps. The distance between the partitions and the reduction screen was held constant at 2.2 m. Each subject received 10 ascending and 10 descending series of trials in one condition, yielding 10 separate estimates of critical aperture width. So that these results would be comparable with those of Experiment 2, we again instructed subjects to judge whether they could walk straight through the opening without turning their shoulders.

At the end of an experimental session, judgments of perceived eye level were obtained. While hidden from view, the experimenter moved a 2-cm × 2-cm marker slowly up the edge of the right partition until the subject said its top edge reached eye level, and then did the same moving downward; these two values were averaged together. This procedure was repeated, yielding two separate estimates of perceived eye level. The distance between perceived eye level and the false floor yielded estimated eyeheight ($e^*_{est}$). In debriefing, we asked subjects in the *raised* condition whether they had noticed the raised floor. An experimental session lasted about an hour.

*Distance estimates.* A different group of 30 subjects participated in this task, 15 subjects in the *flat* condition and 15 in the *raised* condition. The distance between the aperture and the observer was varied across trials, while aperture width was held constant at 35 cm. Five values of aperture distance were used: 1.80, 1.95, 2.10, 2.25, and 2.40 m (6.0, 6.5, 7.0, 7.5, and 8.0 ft). Subjects were instructed to give one verbal estimate in feet and inches of the distance from where they stood to the aperture on each trial. As a reference, a 1-ft ruler was visible on the floor in front of the reduction screen at the subject's feet, oriented parallel to the line of sight. Subjects again covered their view while the aperture distance was changed between trials.

Each aperture distance was presented 10 times in a pseudo-random order, with the restriction that the same distance could not occur more than twice in succession, for a total of 50 trials per subject. Five different orders were randomly assigned to subjects. After the last trial was completed, anthropometric measurements were made, and subjects in the *raised* condition were asked if they had noticed the raised floor. An experimental session lasted about an hour.

Such verbal distance estimates are a standard method for determining perceived distance, although they typically underestimate the range of actual distances (Foley, 1978; Gogel, 1976; Gogel, Hartman, & Harker, 1957). Our purpose here was merely to determine whether such absolute distance estimates are influenced by the eyeheight manipulation. If a change in eyeheight yields a shift in body-scaled judgments of critical aperture width but not absolute estimates of aperture distance, this would provide evidence that passability judgments are not simply based on the perceived absolute distance and visual angle of the aperture but on some independent eyeheight information.

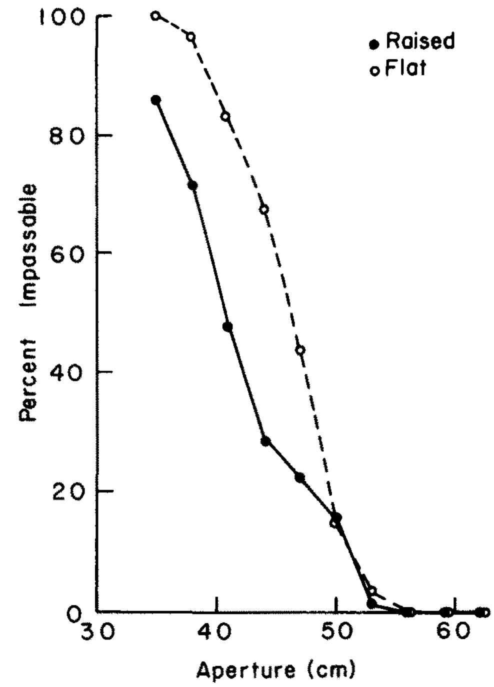


*Figure 6.* Mean percentage of "impassable" judgments as a function of aperture width, in the flat and raised floor conditions. (Each data point represents the mean of approximately 300 trials.)

## *Results and Discussion*

### *Eye Level Estimates*

None of the subjects reported noticing the false floor in the *raised* condition. Hence, our attempt to create the impression of a continuous floor was apparently successful, and subjects were not aware that their effective eyeheight had changed. Although observers did not notice it, the results of the eye level judgments confirmed that estimated eyeheight ($e^*_{est}$), the distance between the eye level estimate and the false floor, decreased when the floor was raised (Table 3). Although the eye level judgments underestimated actual eye level by 6.9 cm ($SD$ = 5.7 cm) or 1.8° of visual angle in the *flat* condition and 7.2 cm ($SD$ = 3.7 cm) or 1.9° in the *raised* condition, the effect of raising the false floor was to reduce the mean estimated eyeheight by 21.8 cm (or $\gamma$ by 4.2°), $t(28) = 6.38$, $p < .001$, precisely the distance the floor was raised (this figure is adjusted for the 1.4-cm difference in mean eyeheight between subjects in the two conditions). Thus, raising the floor led to a corresponding decrease in effective eyeheight, which consequently altered $\gamma$ and the eyeheight ratio, although the observer was unaware of this change.

One possible explanation for the underestimation of eye level is that subjects were relying on the approximate horizon provided by the intersection of the platform with the black backdrop. However, under our conditions this would have produced far greater underestimates of 116.3 cm in the *flat* condition and 99.4 cm in the *raised* condition. The source of the underestimation thus remains unknown, although the phenomenon has also been noted by Sedgwick (1980b) and Mark (1987).

### *Passability Judgments*

The mean percentage of "impassable" judgments as a function of aperture width for both the *flat* and *raised* conditions appears in Figure 6. As predicted, the curve for the *raised* condition shifts leftward so that narrower aperture widths are judged to be passable. An analysis of variance (Aperture × Condition) was performed on subject means of the number of "impassable" judgments. This revealed a main effect of aperture width, $F(10, 280) = 100.51$, $p < .001$, and a main effect of condition, $F(1, 28) = 5.73$, $p < .05$, indicating that subjects in the *raised* condition gave significantly fewer "impassable" judgments overall than those in the *flat* condition. There was also a significant interaction, $F(10, 280) = 4.71$, $p < .001$.

Mean perceptual category boundaries and their standard deviations, calculated from the mean of 10 estimates for each subject, appear in Table 3. As expected, the effect of raising the floor was to reduce the perceived critical aperture width by 4.3 cm, from 44.3 cm to 40.0 cm, with $t(28) = 2.41$, $p < .05$. In other words, observers overestimated the size of the apertures in the *raised* floor condition. Although this shift is not quite as great as the 6.6 cm predicted from the eyeheights of the present subjects, the shortfall is not significant; it might be explained by the fact that eyeheight information conflicted with other intrinsic information such as the ground texture ratio. To normalize the 1.4-cm mean difference in standing eyeheight between subjects in the two conditions, the category boundary can be expressed as a ratio of the observer's standing eyeheight ($A/e$). This yields $A/e = 0.273$ in the *flat* condition and $A/e = 0.248$ in the *raised* condition, with $t(28) = 2.84$, $p < .01$, confirming that the floor manipulation had a significant effect on the category boundary.

However, when critical aperture width is expressed as a ratio of effective eyeheight ($A/e^*$), the ratios converge, as expected if observers are relying on eyeheight information. This yields $A/e^* = 0.281$ in the *flat* condition and $A/e^* = 0.296$ in the *raised* condition, $t(28) = 1.49$, *ns*. These values are very close to the critical ratio of .29 obtained with extreme groups in Experiment 2. Thus, observers appear to rely on a constant eyeheight ratio when judging critical aperture width. The similar performance in Experiments 2 and 3 supports the conclusion that prior exposure to the apparatus did not influence the results in Experiment 2.

### *Distance Estimates*

On the other hand, there was no evidence that raising the floor had an effect on absolute distance estimates. An analysis of variance (Distance × Condition) revealed a main effect of aperture distance, $F(4, 112) = 149.93$, $p < .001$, indicating that actual distance did influence distance estimates, but no main effect of condition, $F(1, 28) = 0.15$, *ns*, and no interaction, $F(4, 112) = 0.35$, *ns*. Thus, whereas the eyeheight manipulation had a significant effect on judgments of aperture width, it had no such effect on judgments of aperture distance. It is possible, of course, that an effect might be found under other viewing conditions or with a body-scaled measure of perceived distance. Our only point here is that under identical conditions, body-scaled judgments of aperture width are influenced by the manipulation of eyeheight, but a standard measure of perceived absolute distance is not. This casts doubt on the explanation that the shift in passability judgments is due to a shift in the perceived absolute distance of the aperture.

This pattern of results thus supports the eyeheight information hypothesis. The fact that the critical ratio

$$A/e^* = 0.29 \tag{10}$$

remained invariant across Experiment 2 and the manipulation of effective eyeheight in Experiment 3 indicates that under static monocular conditions observers rely on intrinsic information that specifies aperture width as a ratio of eyeheight. This particular value obtains under the set of instructions used in Experiments 2 and 3, whereas in free walking, as calculated from the results of Experiment 1, the boundary falls closer to a critical ratio of

$$A/e^* = 0.33. \tag{11}$$

Accounts based on extrinsic information for absolute aperture width and knowledge of shoulder width cannot explain the present results, for they predict no shift in critical aperture width (or, equivalently, a shift in the critical $A/e^*$ ratio).

It also appears that subjects can establish rough eye level (and hence $\gamma$) in a static scene without an explicit horizon, and without utilizing the approximate horizon. The contributions of optical texture convergence and vestibular and muscle proprioception remain open to further investigation.

## General Discussion

The results indicate that humans can perceive whether an aperture affords passage for their particular body size and can utilize intrinsic eyeheight information to do so. The critical point for shoulder rotation at normal walking speeds occurs at an $A/S$ ratio of $\pi_{max} = 1.30$ regardless of body size. At this point a phase transition in behavior occurs from a frontal walking gait to a body rotation. This finding lends support to the similarity hypothesis that such critical points are scale-independent constants for the organism–environment system. Although perceptual judgments underestimate this value slightly, probably due to a difference in instructions, it is apparent that the perceptual category boundary can be rationalized with reference to constraints on action. The findings are similar to those of Warren (1984), in which judgments of the climbability of stairways by short and tall observers closely corresponded to their actual critical and optimal riser heights.

It is interesting to note that in studies of visually guided jumping by frogs, Ingle and Cook (1977) found that the frequency of jumping through a near aperture dropped sharply as aperture width approached the frog's largest frontal dimension, its head width; this boundary shifted systematically with frogs of different sizes (Ingle, personal communication). Lock and Collett (1980) reported a similar boundary for the toad at an aperture width that roughly corresponded to the width of the toad's head. Although the biomechanics of walking in humans are quite different from those of jumping in the frog and toad, some analogous interspecies constraints apply, including a range of lateral body motion and a proportional safety margin. This leads one to speculate about the existence of universal pi numbers or allometric constants for affordances, comparable to the allometric relations that have been found for morphology, physiology, and locomotion (McMahon & Bonner, 1983; Pedley, 1977). We would expect to find adaptations in critical aperture width accompanying rapid intra-individual changes in body size, as in pregnancy, adolescence, or experimental manipulations of body width, according to the general pi number of 1.30. The ontogeny of this critical value can also be explored in infants who are learning to crawl or walk (McKenzie & Spelke, 1987; Palmer, 1986).

What type of optical information are such body-scaled perceptual judgments based on? The present results offer some preliminary answers to this question. First, static monocular information appears to be sufficient for consistent judgments of passability, and kinematic information appears unnecessary. Second, the results indicate that observers can utilize static intrinsic information that specifies aperture width as a ratio of eyeheight, at least under the present conditions. It is an open and perhaps untestable question as to whether they actually *do* use such body-scaled information under natural conditions. However, the extrinsic alternatives are problematic: Accommodation and convergence are ineffective at distances greater than 1 m; binocular disparity does not provide absolute information; and motion parallax, like accommodation and convergence, yields poor estimates of absolute distance. Thus, although the static monocular conditions of Experiment 3 were artificially restrictive, the evidence suggests that the extrinsic information they eliminated may not be usable for absolute size and distance judgments anyway. Given that at least one example of intrinsic information is sufficient and that the extrinsic cues are insufficient, then, barring the discovery of other extrinsic variables, it is reasonable to argue that intrinsic information may generalize to natural viewing conditions. Whether intrinsic information other than the static eyeheight ratio, including kinematic variables such as the height of the focus of expansion, is also sufficient for body-scaled size judgments remains an open question. That the motion condition in Experiment 2 did not yield better performance than the static condition indicates that any kinematic information is at best redundant with static eyeheight information. In sum, the present study demonstrates that the static eyeheight ratio is sufficient for passability judgments and may have implications for more natural viewing conditions.

There remains the possibility that observers rely on extrinsic information for absolute aperture width, compare it with explicity perceived eyeheight, and determine critical aperture width according to $A/e^* = 0.29$. On this account, subjects in Experiment 3 could have cognitively compensated for the change in eyeheight if they had known about the raised floor and would not have shown a shift in the category boundary. However, Mark (1987) has found similar results for judgments of maximum sitting height and maximum climbable stair height when effective eyeheight was manipulated with the observer's knowledge by strapping 10-cm blocks to their feet. For initial judgments, there were shifts in the critical seat and stair boundaries with the change in viewing condition, but the effective eyeheight ratios remained constant, supporting the use of eyeheight information. Thus, even when observers knew their eyeheight had been changed, they did not cognitively compensate for the manipulation to cancel the boundary shift. However, after observers walked briefly on the blocks, judgments adapted to reflect the critical points of their new sitting and climbing capabilities. This suggests that perceptual adaptation to new critical points that result from changes in body dimensions is quite rapid and can actually occur without physically engaging in each implicated action.

The notion of such body-scaled information is appealing on two accounts. First, as noted, the ability of perceivers to utilize extrinsic information under such conditions is problematic. Second, intrinsic information is scaled to the perceiver's action system and could thus directly regulate action. Given that an affordance relation such as $A/S$ is optically specified by eyeheight information, its critical point of $A/S = 1.30$ is specified by a particular margin value of the eyeheight ratio, $A/e = 0.33$. Thus, the phase transition between frontal walking and body rotation could be regulated by this optical margin value. This is consistent with the view that the action system adopts special-purpose, functionally specific modes of organization, each regulated by particular optical variables with characteristic margin values (Reed, in press; Warren, in press). Different actions involve different critical points and may be regulated by different task-specific information, rather than by a single general-purpose visual representation of the objective environment. Because critical points have a natural basis in the dynamics of the ecosystem, the optical margin values that specify them can be discovered through active exploration in the course of perceptual learning or development, apparently quite rapidly. Thus, the present results support the notion that an affordance such as a passable aperture, which is simply a relation between environmental and body dimensions, can be perceived via information that specifies that relation.

The analysis of affordances presented here also has applications to problems in ergonomics and environmental design (Warren, 1984, 1985). For example, the currently accepted design standard for the minimum width of horizontal circulation spaces such as corridors, doorways, and hatchways is 21 in. (53.3 cm) per pedestrian width (Ramsey & Sleeper, 1970). However, it is apparent from Figure 1 that apertures of this size induce shoulder rotation is over 97.5% of the male population, which is not only inconvenient but potentially hazardous. Based on the critical pi number of 1.30 and the 95th percentile for male shoulder width of 49 cm, the present results suggest a design recommendation of 25 in. (63.7 cm), as a minimum for horizontal circulation spaces. This will safely accommodate 95% of the population without inducing shoulder rotation. Determining critical pi numbers for other basic activities would permit similar body-scaled design standards to be derived from anthropometric data for a particular target population.

In sum, the results support previous findings that observers can make body-scaled visual judgments of environmental properties that are relevant to action and indicate that they can do so on the basis of intrinsic optical information. We interpret this finding to suggest that observers can perceive the affordance of passability in order to guide locomotion.

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