

Perceiving Affordances: Visual Guidance of Stair Climbing

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How do animals visually guide their activities in a cluttered environment? Gibson (1979) proposed that they perceive what environmental objects offer or *afford* for action. An analysis of affordances in terms of the dynamics of an animal-environment system is presented. Critical points, corresponding to phase transitions in behavior, and optimal points, corresponding to stable, preferred regions of minimum energy expenditure, emerge from variation in the animal-environment fit. It is hypothesized that these points are constants across physically similar systems and that they provide a natural basis for perceptual categories and preferences. In three experiments these hypotheses are examined for the activity of human stair climbing, by varying riser height with respect to leg length. The perceptual category boundary between "climbable" and "unclimbable" stairs is predicted by a biomechanical model, and visually preferred riser height is predicted from measurements of minimum energy expenditure during climbing. It is concluded that perception for the control of action reflects the underlying dynamics of the animal-environment system.

How do humans and animals visually control their actions with respect to the surfaces, objects, and events of the local environment? During locomotion, for example, an animal successfully adopts a path through cluttered terrain, selecting surfaces that will support its weight and posture, avoiding obstacles and precipitous drops, and tailoring its gait to

uneven ground. Recent work by Riccio and E. J. Gibson (1983) has shown that even infants who are just learning to walk perform discriminative actions with regard to traversible and nontraversable surfaces. What is the relationship between perception and action that makes such oriented activity possible?

Affordances

J. J. Gibson (1958, 1977, 1979, 1983) proposed that animals visually guide their behavior by perceiving what environmental objects offer or afford for action. An *affordance* is the functional utility of an object for an animal with certain action capabilities. Specifically, it is the combination of environmental properties that supports some activity for a particular animal: "The affordance of anything is a specific combination of its substance and its surfaces taken with reference to an animal" (1977, p. 67). Affordances are thereby based in material properties of the animal and the environment and exist whether or not they are being perceived.¹

The research reported here was performed as part of a doctoral dissertation at the University of Connecticut, with support from a National Science Foundation Graduate Fellowship and the University of Connecticut Research Foundation. Preparation of this article was supported in part by a postdoctoral National Research Service Award (NS07111-01) from the National Institutes of Health, sponsored by the University of Edinburgh.

I would like to thank Robert Shaw, Michael Turvey, Jim Todd, Peter Kugler, David Lee, Scott Kelso, Len Mark, and Sverker Runeson for their consultation and comments on earlier drafts of the manuscript. My gratitude also extends to George von Cochran for help in securing the rather novel equipment, Tova Clayman, Linda Rieser, and Andy Warner for their assistance in the data collection, and Linda Ferrell, Jean Savage, and Diane Hargreaves for their aid with the research and preparation of the manuscript.

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¹ Thus, an affordance does not change with the need or state of the perceiver. This contrasts with von Uexküll's (1934/1957) concept of the *Umwelt*, Lewin's (1935)

To determine whether a given path affords locomotion, the behaviorally relevant properties of the environment must be analyzed in relation to relevant properties of the animal and its action system: surface rigidity in relation to body mass, surface contours in relation to gait, passage width in relation to body dimensions, and so on. Thus, if an animal guides its activity by perceiving affordances, it must be capable of perceiving the relationship between environmental properties and properties of its own action system. This implies an intrinsic or "body-scaled" metric for the analysis of visual information and perceptual-motor control (Fitch & Turvey, 1978; Lee, 1980; Warren & Kelso, 1984; Warren & Shaw, 1981) as opposed to an extrinsic or absolute metric.

A number of studies in the literature exemplify the perception of affordances by a variety of species. In studies of visually guided jumping in frogs, for example, Ingle and Cook (1977) found that the frequency of jumping through an aperture dropped from 75% to 25% when the width of the opening approached 1.3 times the width of the frog's head. Thus, the frog apparently detects apertures that afford passage for its specific body size. In a study of the attack behavior of the praying mantis, Holling (1964) was able to predict the prey radius that elicited the highest frequency of attack responses, based on an analysis of the grasping capabilities of the insect's forelimb. Hence, the mantis perceives the size of prey that optimally affords grasping. A similar result has been found for human grasping (Hallford, 1983).

concept of valence, and Koffka's (1935) concept of demand character. Although affordances themselves do not change with need, an affordance may be selectively attended to. When a rock of a certain size, shape, and weight affords both throwing and pounding, the fact that a person in need of a hammer attends to certain aspects of the rock does not alter its properties or its utility for both activities (see Gibson, 1979, p. 138-139; Gibson, 1982, p. 410). Affordances bear a closer resemblance to Tolman's (1932) concept of sign gestalt, the external relations among objects and their properties that support purposive behavior. Gibson argues, however, that such relations can be directly perceived without a prior association, set, or means-end readiness. It is interesting that both Gibson and Tolman were students of Holt.

Finally, Branch (1979) has observed that South African east-coast limpets (clams) shorter than 30 mm in length retreat from a predatory whelk, whereas larger individuals attack the predator by battering it with their shell. This boundary shifts to 43 mm for west-coast limpets, where the whelks are larger. Thus, the affordances of attack and retreat are determined by the relative size of predator and prey.

Such affordances are grounded in material properties of the animal and its environment (see Turvey, Shaw, Reed, & Mace, 1981). These properties may be described not only by geometric variables, such as the object sizes and body dimensions required for grasping or passing through apertures, but also by kinetic variables such as mass, force, friction, elasticity, and work, which are relevant to metabolic energy exchanges (Warren, 1983; Winter, 1979). With regard to human locomotion, for example, the elasticity or compliance of the surface of locomotion has been shown to affect energy expenditure and top running speed (McMahon & Greene, 1978; Pandolf, Haisman, & Goldman, 1976; Soule & Goldman, 1972). Thus, the dynamics of the animal-environment system defined by geometric and kinetic variables determine the possible activities and energetically optimal courses of action in any situation—i.e., what the situation affords for action. A specific set of values of the animal and environmental properties that are relevant to a given activity will be called a *dynamic animal-environment fit*.² The purpose of the present study is to offer a precise description of the animal-environment fit for the activity of stair climbing and to determine whether perceptual categories and preferences relevant to the guidance of this activity reflect the underlying dynamics of the system.

² An affordance constitutes one perspective on the organism-environment fit, construing environmental properties with reference to an organism. Turvey and Shaw (1979) have introduced the complementary term *effectivity* for the action capabilities of an organism within a particular environment. This provides the reciprocal perspective on the organism-environment fit, construing organism properties with reference to the environment.

Stair Climbing

The stairway is a basic modification of the natural environment to scale it to human use. Flights of stairs are found in many early cultures from neolithic Cyprian villages to the ruins of early Egyptian and Mesopotamian buildings (see Fitch, Templer, & Corcoran, 1974; and Templer, 1975, for an architectural survey). The activity of stair climbing is a special case of human bipedal locomotion that is metabolically demanding, requiring up to 15 times the energy expended in walking the same distance on the level. Unlike simple grade walking, the stride length and lift work done on each step are prescribed by the stairway's dimensions, so that an optimal gait cannot be freely adopted. Thus, to a great extent the metabolic efficiency of climbing is determined by the fit between the dimensions of stairway and climber.

The precise formulation of a golden mean for stairway dimensions has been a matter of dispute since the time of the Greeks, with recommendations offered by Vitruvius in the 1st century BC (1960), Alberti (1485/1955), and Palladio (1570/1965). The first formal model was offered by the French architect Francois Blondel (1675–1683), who reasoned that since a comfortable pace length was 24 French royal in. horizontally and 12 in. vertically, 2 in. should be subtracted from the tread depth (T) for every inch of riser height (R):

$$2R + T = 24 \text{ in.} \quad (1)$$

This idea was widely adopted and remains intact in many of today's building codes, such as the National Fire Code (1978; see related versions in National Building Code, 1976; Ramsey & Sleeper, 1970). Aside from their dubious biomechanical basis, such rules are indeterminate, permitting a range of riser and tread combinations that allows the architect to adapt stair dimensions to the demands of the space, but not always to the action systems of climbers. The dimensions of actual stairways vary widely, from the short risers and oversized treads of "monument steps," employed for their sweeping visual impact, to the high risers and narrow treads of many basement and attic stairs,

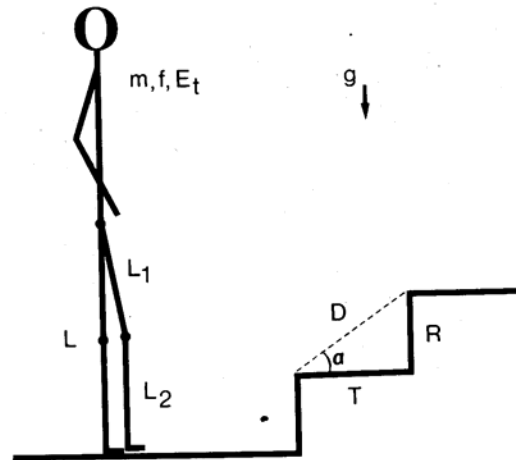


Figure 1. Variables of the climber-stair system: R = riser height, T = tread depth, D = stair diagonal, α = pitch, g = gravitational acceleration, L = leg length, L_1 = thigh length, L_2 = lower leg length, m = body mass, f = step frequency, E_t = energy expenditure per unit time.

used to conserve floor space. How might the fit between stairway and climber be measured, and how might the limiting and optimal designs for stairways be determined? (The following approach to this problem was inspired by the work of Kugler, Kelso, & Turvey, 1980, 1981; Kugler & Turvey, in press; Iberall, 1977, 1978; and Shaw & Cutting, 1980).

The functionally relevant variables of the climber-stair system are illustrated in Figure 1. A relationship among these variables can be formalized as an undetermined function β (cf., Rosen, 1978b):

$$\beta(R, D, L, w, f, E_t) = 0. \quad (2)$$

Rearranged, this equation states that the rate of energy expenditure during climbing (E_t) is some function of step frequency (f) and the four fixed variables of riser height (R), stair diagonal (D), leg length (L), and body weight (w).³

³ The other variables in Figure 2 can be derived from this set: tread depth (T) and stair pitch (α) trigonometrically from riser height and the stair diagonal, and thigh length (L_1) and lower leg length (L_2) from leg length by anthropometric constants (see Experiment 1); weight is related to mass by $w = mg$. The stair diagonal was chosen for its direct relevance to the stride length of the climbing gait.

To formally characterize an affordance, Gibson (1979) suggested that environmental properties "have to be measured relative to the animal," (p. 127–128), rather than measured as neutral properties in arbitrarily defined or *extrinsic* units. This can be achieved by a method of *intrinsic* measurement, in which one part of a system is taken as a "natural standard" against which a reciprocal part of the system (having the same dimensions) is measured (Bunge, 1973; Warren, 1983). Thus, an animal property *A* may be taken as a standard for measuring an environmental property *E*. Procedurally, if *A* and *E* are measured in the same conventional units and are expressed as a ratio, the units cancel and the result is a dimensionless (i.e., unitless) number that uniquely expresses a particular animal–environment fit:

$$\pi = E/A. \quad (3)$$

Such dimensionless ratios of system variables are called *pi numbers* and may be derived using the methods of dimensional analysis (Buckingham, 1914; Rosen, 1978b; Schuring, 1977; Stahl, 1961, 1963).⁴

The climber–stair system can be described by finding dimensionless ratios of the variables in Equation 2 by this method (Warren, 1983). Two of these ratios are pertinent to the present study:

$$\pi_1 = R/L, \quad (4)$$

an intrinsic measure of riser height as a proportion of leg length, and

$$\pi_2 = D/L, \quad (5)$$

an intrinsic measure of the stair diagonal as a proportion of leg length. Specific values of these *pi numbers* capture the geometry of a particular fit between stairway dimensions and the climber's body dimensions.

As the animal–environment fit is varied, the affordances of the situation are altered and qualitative features of behavior emerge at specific values of *pi*: *critical points*, corresponding to phase transitions in behavior at affordance boundaries, and *optimal points*, corresponding to stable, preferred regions of minimum energy expenditure, or "best fit" affordances. For example, as riser height is increased with respect to leg length, a critical point is reached at which the stair is too high

to afford bipedal climbing, and the climber must shift to a quadrupedal (hands-and-knees) gait. Similarly, as riser height is varied with respect to leg length, an optimal point should occur, yielding minimum energy expenditure per vertical meter of travel—a candidate for the best fit between climber and stair. Thus, affordance boundaries and optima are condensed out of variation in the dynamic fit between animal and environment. These landmarks may be predicted on the basis of biomechanical models, or they may be determined empirically. In the present study, the ratio *R/L* is varied in this way while *D/L* is held constant.

To illustrate how optimal and critical points emerge from the dynamics of a system, consider the occurrence of preferred velocities and gait transitions during locomotion. First, Hoyt and Taylor (1981) measured energy expenditure per meter in horses during forced locomotion on a treadmill and found optimal velocities with minimum metabolic cost for walking, trotting, and galloping. They then observed that these horses adopted precisely these velocities in each gait during free over-ground locomotion. Ralston (1958; Zarrugh, Todd, & Ralston, 1974) has made the same observation for human walking. Thus, preferred behavior tends to correspond to the energetic optimal point. Second, the trot–gallop transition also occurs at a characteristic velocity, which can be predicted across species as a function of body weight (Heglund, Taylor, & McMahon, 1974; McMahon, 1975). For the horses in Hoyt and Taylor's (1981) study, this "allometric" equation yields a value of 5 m/s for the trot–gallop transition, which closely agrees with the empirically determined velocity at which galloping became energetically more efficient than trotting (4.7 m/s). These results suggest that both stable gaits and gait transitions can be accounted for by dynamic optimal and critical points.

In the case of stair climbing, because the *pi number* *R/L* expresses an intrinsic geometric relationship between riser height and

⁴ Conversely, for effectivities, environmental properties are taken as standards against which organism properties are measured, and the resulting ratios are the inverse: *A/E*.

leg length, these critical and optimal values should be constant regardless of the absolute size of the climber. That is, for any two physically similar systems (governed by the same Equation 2), their critical and optimal points occur at equal values of π , independent of scale (Rosen, 1978a, 1978b). For example, in studies of folk norms for hand tools, Drillis (1963) found that scaling tools as a constant proportion of the user's body dimensions, such as axe handle length equal to the length of the user's arm, preserved the most energetically efficient design over variations in body size. In this case, a constant π value preserved the optimal affordance over changes in scale.

Perception and Action

With this description of an affordance in terms of the animal-environment fit and its landmark critical and optimal points in mind, let us return to the original question about perception for the control of action. If the visual guidance of activity is to be successful and economical, the perceiver presumably must be capable of detecting both the limits on action and the most efficient paths of action. The central hypothesis of the present study is that perceptual performance reflects the underlying dynamics of activity for the animal-environment system, specifically, that perceptual category boundaries correspond to critical points and perceptual preferences correspond to optimal points in the system. Second, according to the similarity hypothesis, these perceived points are constants over scale changes in the system. The hypothesized parallelism between perception and action implies that predictions can be made about perceptual performance from an analysis of action and vice versa.

In the case of stair climbing, this means that the perceptual category boundary between bipedally "climbable" and "unclimbable" risers should correspond to critical riser height, as estimated by a biomechanical model, and that this value should be the same for short and tall observers. Experiment 1 was designed to test this prediction. Similarly, perceptual preferences for riser height should correspond to the energetically optimal riser, and again this value should be constant

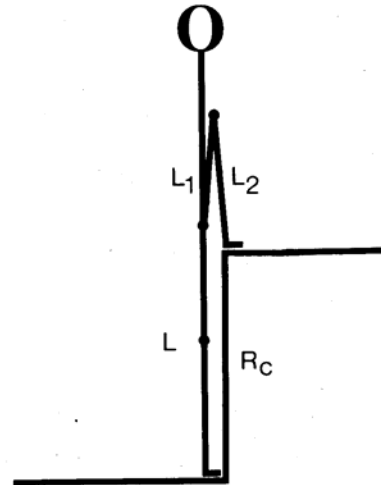


Figure 2. Biomechanical model of critical riser height, showing idealized maximum leg flexion.

for short and tall observers. In Experiment 2, optimal riser height was determined empirically by measuring the oxygen consumption of short and tall climbers during ascent on a motor-driven stairmill, while in Experiment 3 visual preferences for riser height were examined.

Experiment 1: Visual Perception of Critical Riser Height

The first experiment examined the hypothesis that the perceptual category boundary between climbable and unclimbable risers corresponds to critical riser height.

Maximum or critical riser height R_c can be estimated from a simple biomechanical model of climbing. To raise the body in a gravitational field, a climber must be able to position his or her center of mass directly above the base of support (the top foot). As riser height increases with respect to leg length, a critical point, $\pi_c = R_c/L$, is reached at which this is no longer possible, and the climber must shift from a bipedal to a quadrupedal (hands-and-knees) gait.

This ratio can be approximated by the riser height at which the leg would be completely flexed, with all segments vertical (see Figure 2). Thus,

$$R_c = L + L_1 - L_2. \quad (6)$$

Table 1
*Anthropometric Data for Participants
in Experiment 1*

Group	Height	Eyeheight	Leg	L. leg
Short				
<i>M</i>	163.67	152.92	76.00	42.98
<i>SD</i>	2.50	2.75	2.01	1.22
Tall				
<i>M</i>	189.75	179.13	91.33	50.39
<i>SD</i>	3.56	3.78	3.14	1.47

Note. L. leg = lower leg length. Measurements are in cm. *N* = 12 per group.

Based on limb segment measurements of participants in the present study (Table 1), critical riser height can be calculated for this group as a proportion of leg length:

$$R_c = L + .44L - .56L = .88L \quad (7)$$

or

$$\pi_c = R_c/L = .88. \quad (8)$$

Because the lower and upper leg proportions are approximately constant over climbers of different heights, this π value is constant as well, reflecting the necessary geometry for raising the body's center of mass in a gravitational field.

Thus, the perceptual category boundary between bipedally climbable and unclimbable risers, symbolized R_c^*/L , should correspond to .88 for both short and tall observers. To test this hypothesis, slides of stairs with risers of 20 in.–40 in. (50.8 cm–101.6 cm) were presented to short and tall observers, and judgments of climbability were obtained.

Method

Subjects. Two groups of male college students, selected to represent the 2nd and 98th percentiles of normal adult male heights (Dreyfuss, 1970), were paid to participate in the experiment. The Short group contained 12 participants with a mean height of 5 ft 4.4 in. (163.7 cm) and the Tall group contained another 12 with a mean height of 6 ft 2.7 in. (189.8 cm). After the experimental session, the following body measurements were made using a metric anthropometer (Weiner & Lourie, 1969): standing height, sitting height, eye height, and knee height (to tibial notch). Leg length was calculated by subtracting sitting height from standing height, yielding the distance from the sole of the foot to the ischium (bottom of the pelvis), rather than to the head of the femur. Anthropometric data are presented in Table 1.

Displays. Black-and-white slides were taken of a

single adjustable wooden stairway in five configurations: $R_s = 20, 25, 30, 35$, and 40 in. (50.8 cm to 101.6 cm), with $D = 42$ in. (106.7 cm); tread depth and pitch varied accordingly. The stairway had two steps with white risers and gray treads; it was photographed from a distance of 14 ft (4.27 m) with camera heights of 5 ft (1.52 m) and 6 ft (1.83 m), corresponding to the eye heights of the Short and Tall groups. As slides eliminated intrinsic optical information for the height of stairs relative to the height of the observer, additional scaling information was provided by placing a reference object in the slide and in the testing room—in this case a wooden desk chair standing with its back up against the bottom riser.

The slides were projected from a height of 5 ft (1.52 m) onto a wall in the testing room, with the reference chair standing to the right of the 4-ft \times 6-ft (1.22 m \times 1.83 m) image. Short and Tall participants, run in separate groups of one to six, viewed the appropriate set of slides while standing at a distance of 14 ft (4.27 m). This presented approximately the same visual perspective on the chair in the testing room as appeared in the slides.

Procedure. Five slides of each of the five riser heights were arranged in random order and presented once in each direction, for a total of 50 trials. The test sequence was preceded by two practice slides showing the endpoints of the test series ($R_s = 20$ in. and 40 in., or 50.8 cm and 101.6 cm). Observers were instructed to judge whether each stairway looked climbable or unclimbable "in the normal way, without using your hands or knees" and to mark their responses on an answer sheet. They then rated their confidence in the judgment on a scale of 1 to 7, where 1 was *least sure* and 7 was *most sure*. The instructions emphasized the height of the individual stairs as the relevant factor and related riser height to chair height in the two practice slides, which were identified as the endpoints of the series. Each test slide was presented for approximately 8 s, during which time both a climbability judgment and a confidence rating were made. The experiment lasted about 15 min.

Results

Categorization judgments. The mean percentage of "climbable" judgments is plotted as a function of riser height for each group in Figure 3. The group curves appear similar in shape, but the Tall curve is shifted to the right of the Short curve. A two-way repeated measures analysis of variance (Riser Height \times Group) was performed on individual scores. A main riser effect showed that the overall decrease in "climbable" judgments as a function of riser height was significant, $F(4, 88) = 193.14$, $p < .001$, and a main group effect demonstrated that Tall participants gave significantly more "climbable" judgments than did Short participants, $F(1, 22) = 38.43$, $p < .001$. The interaction was also significant, $F(4, 88) = 16.85$, $p < .001$.

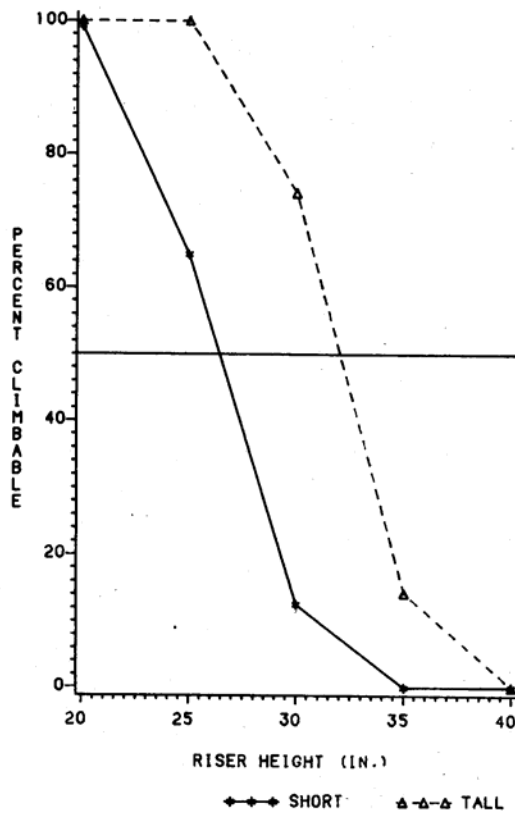


Figure 3. Mean percentage of "climbable" judgments as a function of riser height for each group.

The percentage of "climbable" judgments dropped from a true ceiling (100%) to a true floor (0%) for every participant, with a mean drop of 71.5% per series interval across the 50% "chance" line. The riser height at which the group curve crossed chance was taken to indicate the perceptual category boundary, and was equal to 26.43 in. (67.13 cm) for the Short group and 32.02 in. (81.33 cm) for the Tall group.

To examine the similarity hypothesis, the data are replotted on an intrinsic R/L axis in Figure 4, where L is the mean leg length for the corresponding group. The resulting curves are nearly congruent, the intrinsic scaling of riser height eliminating group differences. The category boundaries are also equivalent, yielding

$$R_c^*/L = 67.13 \text{ cm}/76.00 \text{ cm} = .88 \quad (9)$$

for the Short group, and

$$R_c^*/L = 81.33 \text{ cm}/91.33 \text{ cm} = .89 \quad (10)$$

for the Tall group. These values closely correspond to the critical ratio of .88 predicted by the biomechanical model (Equation 8).

Confidence ratings. Confidence ratings were intended to provide a converging measure of the perceptual category boundary, on the assumption that uncertainty about the judgment would be greatest at or near the boundary, and hence confidence at a minimum. Mean confidence ratings for each group are plotted against riser height in Figure 5. A two-way repeated measures analysis of variance revealed a main effect of riser height, $F(4, 88) = 57.31, p < .001$, no main group effect, because the two U-shaped curves cover the same range of rating values, $F(1, 22) = 0.87, p > .05$, but a significant interaction,

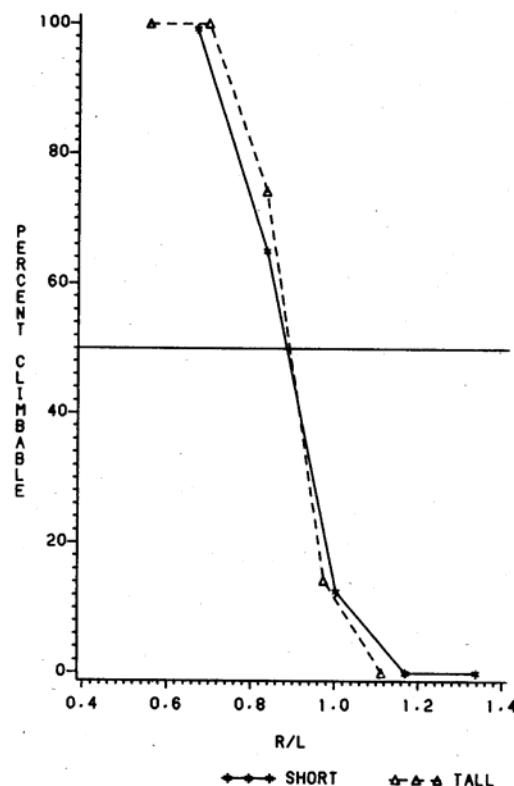


Figure 4. Intrinsic plot: mean percentage of "climbable" judgments as a function of R/L for each group.

$F(4, 88) = 24.65$, $p < .001$, demonstrating a nonparallelism between the group curves.

The precise locations of the minima of the curves in Figure 5 are obscured by the coarseness of the riser height series used in the experiment. To obtain a more precise estimate, an average of each participant's lowest rated riser was calculated, yielding means of 26.25 in. (66.68 cm, $SD = 5.74$ cm) for the Short group and 31.67 in. (80.44 cm, $SD = 8.28$ cm) for the Tall group—very near the judgment boundaries of 26.43 in. and 32.02 in. (67.1 cm and 81.3 cm), respectively, lending further support to these values as perceptual category boundaries.

Plotting the confidence ratings on an intrinsic R/L axis in Figure 6 yields nearly congruent curves, as with the categorization

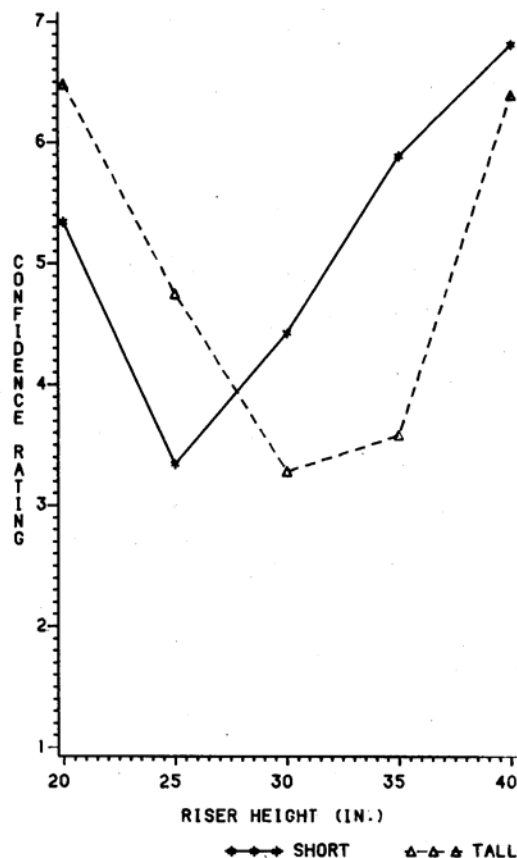


Figure 5. Mean confidence ratings as a function of riser height for each group.

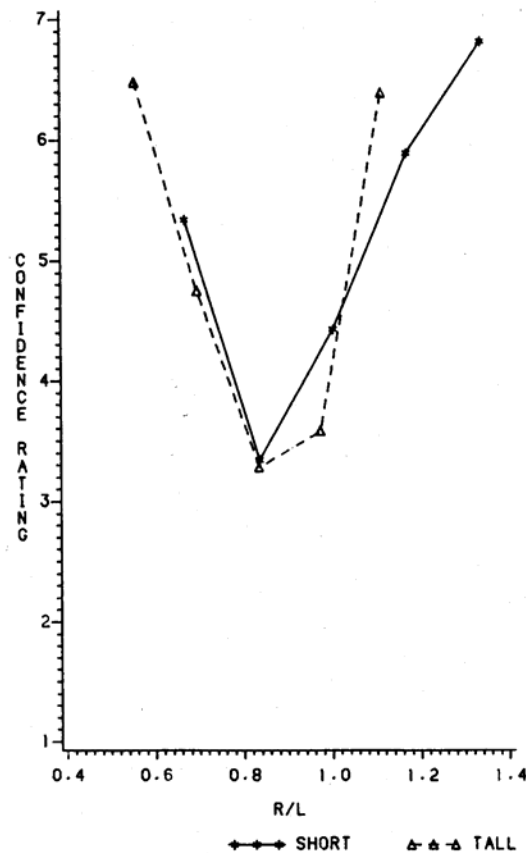


Figure 6. Intrinsic plot: mean confidence ratings as a function of R/L for each group.

data. The minima may also be expressed intrinsically:

$$R_c^*/L = 66.68 \text{ cm} / 76.00 \text{ cm} = .88 \quad (11)$$

for the Short group, and

$$R_c^*/L = 80.44 \text{ cm} / 91.33 \text{ cm} = .88 \quad (12)$$

for the Tall group. These values correspond to the critical value of .88 predicted by the biomechanical model.

Discussion

The results demonstrate that both short and tall observers judge stairways as unclimbable at a riser height that is a constant proportion of their leg lengths. Categorization judgments and confidence ratings converge on a perceptual category boundary of $R_c^*/$

$L = .88$, the value predicted by the biomechanical model. These results lend strong support to the hypothesis that perception is anchored in the biomechanics of activity and to the similarity hypothesis that functional category boundaries are constant over changes in scale. Thus, a general critical π value for perception and action in stair climbing appears to be justified:

$$\pi_c = .88. \quad (13)$$

The affordance boundary between climbable and unclimbable stairways and the accompanying perceptual category boundary can thus be seen to emerge from the dynamics of the animal-environment system. Analyzing the biomechanical basis for critical riser height and identifying intrinsic optical information specific to R/L (see General Discussion) would provide the makings of a lawful account of perceptual categories without an appeal to mediating constructs such as mental categories or concepts.

The view that perceptual categories have a natural basis in critical points of dynamic systems may be generalized to other studies of categorization. Some research on "mental" or linguistic categories is directly related to the affordances of objects for certain activities. For example, Labov (1973) varied the height-to-width ratio in drawings of cuplike objects and obtained categorizations of bowl, cup, and vase. These judgment boundaries may have a perceptual rather than conceptual basis, because the categories are intrinsically defined by the ratio of container dimensions that is required to hold a flower upright or to permit a spoon to hold food or liquid. These functional requirements have consequences for the shape and formal similarity of category members and, hence, for their visual specification.

Other research has focused on the categorization of natural objects, such as species of plants and animals. In such cases, the critical point occurs in the dynamics of an evolving species, leading to speciation and leaving its mark in the distinctive morphology and formal similarity of species members (cf. Ghiselin, 1981). For example, Cerella (1979) studied abstract concepts of leaf patterns in the pigeon, and found quickly learned and

highly reliable discrimination of oak leaves from those of other species. Rather than ascribing such categorization behavior to a priori concepts or classification strategies, the informational basis for categorization yielded by the critical point must be sought: the higher order invariant pattern that underlies the staggering variety of oak leaves, which pigeons can apparently detect in a single exemplar. In sum, many category boundaries may be perceptual in origin, having a basis in information that specifies critical points in affordances and other natural systems.

The first experiment provided evidence that the perceptual category boundary corresponds to critical riser height; the remaining experiments go on to examine optimal riser height.

Experiment 2: Energetics of Optimal Riser Height

As riser height is varied with respect to leg length, an optimal point should occur, yielding minimum energy expenditure per vertical meter of travel. In Experiment 2 I sought to determine this optimal riser height empirically by measuring energy expenditure during climbing.

Optimal riser height R_o is a consequence of two factors: First, as risers become lower, more step cycles are required to ascend a given distance; hence total muscle activity and energy expenditure increase. On the other hand, as risers become higher relative to leg length, energy expenditure increases due to greater flexion at the knee and hip, and consequently, there is greater initial muscle length (Hill, 1930; Morrison, 1970), greater co-contraction for joint stabilization (Joseph & Watson, 1967; Morrison, 1969; Townsend, Lainhart, Shiavi, & Caylor, 1978), and higher raising of the lower limbs during the swing phase (Cappozzo & Leo, 1974). The combination of these two factors should yield an optimal ratio of R_o/L with minimum energy expenditure.

A number of studies have compared the metabolic cost of climbing on stairways with different dimensions, by means of either oxygen consumption (Bruce, Floyd, & Ward, 1967; Corlett, Hutcheson, DeLugan, & Ro-

Table 2
Anthropometric Data for Participants in Experiment 2

Subject	Age	Weight (kg)	Height (cm)	Eyeheight (cm)	Leg (cm)	L. leg (cm)	$\dot{V}O_2\text{max}$ (ml/kg-min)	Percentile	R_o/L
Short									
RW	18	63.8	160.9	150.1	73.3	42.7	57.6	90	.26
AD	18	44.7	161.0	150.6	75.7	43.6	55.9	85	.27
LS	19	53.1	159.8	148.9	74.5	43.2	47.5	60	.26
<i>M</i>			160.57	149.87	74.50	43.17			
Tall									
DB	19	73.5	193.1	182.3	95.3	53.1	59.3	95	.25
EF	18	89.6	196.7	181.5	93.9	53.3	52.5	80	.32
TC	18	84.9	191.5	177.4	92.7	51.6	57.6	90	.24
<i>M</i>			193.77	180.40	93.97	52.67			

Note. L. leg = lower leg length; $\dot{V}O_2\text{max}$ = maximal aerobic power; R_o/L = optimal riser height to leg length ratio.

gozenski, 1972; Hirschberg & Ralston, 1965; Keiser, 1960; Richardson, 1966; Shinno, 1971) or heart rate (Corlett et al., 1972; Ward & Beadling, 1970; Ward & Randall, 1967). The average optimal stairway over these studies had dimensions of $R = 6.8$ in. (17.4 cm), $D = 13$ in. (32.8 cm), $T = 11$ in. (27.8 cm), and $\alpha = 32^\circ$. However, these investigators ran relatively few (two to six) conditions without systematically varying stair dimensions, often confounded ascent and descent in the same test trials, and did not report the body dimensions of subjects.

The most complete study was performed by Lehmann and Engelmann (1933), who ran 15 conditions and found a well-defined minimum of 10 cal/kg-m on a stairway with $R = 7.1$ in. (18 cm), $D = 13.4$ in. (34 cm), $T = 11.4$ in. (29 cm), and $\alpha = 29^\circ$. However, ascent and descent were again confounded, and body dimensions were not reported. Templer (1975) employed a large multiple regression approach but obtained rather unsystematic results with no clearly defined minima. This could be due to his variation of both vertical velocity and step frequency across conditions, the measurement of net instead of gross energy expenditure (see Ralston, 1976), or allowing climbers to use a handrail. The only known study to report body heights is that of Benedict and Parmenter (1928), from which the leg lengths of their female subjects can be estimated using anthropometric norms (Dreyfuss, 1970). Optimal leg length for the one stairway tested

($R = 8.2$ in. or 21 cm, $D = 13.8$ in. or 35.1 cm) was approximately 83 cm, suggesting an optimal ratio of $R_o/L = .25$.

In Experiment 2, optimal riser height was determined empirically by measuring the oxygen consumption of short and tall climbers during ascent on an adjustable motor-driven stairmill. The similarity hypothesis predicts that R_o/L should be a constant over climbers with different leg lengths, because within limits, any similar limb systems progressing through the same geometric configurations should require the same energy expenditure, given that body mass and step frequency are equated. This optimal point was then used to predict perceptual preferences for riser height in Experiment 3.

Method

Subjects. Six male college students, none of whom were in the perceptual studies, were paid to participate in this experiment. The three Short participants had a mean height of 5 ft 3.2 in. (160.6 cm), and the three Tall participants had a mean height of 6 ft 4.3 in. (193.8 cm). Maximal aerobic power ($\dot{V}O_2\text{max}$) was estimated from recovery heart rate using a step test (McArdle, Katch, & Katch, 1981); the participants ranged from the 60th to the 95th male population percentiles. None of the participants were smokers or team athletes. Anthropometric data appear in Table 2.

Equipment. Test trials were run on an adjustable stairmill driven by a variable-speed motor (the same one described in Richardson, 1966, and Fitch, Templer, & Corcoran, 1974). A participant could climb "in place" at a specified step frequency for an indefinite period of time and perform an amount of work equal to that on a fixed stairway. Six stairway conditions were designed to

cover the typical architectural range of riser heights: $R_s = 5, 6, 7, 8, 9$, and 10 in. (12.7 cm to 25.4 cm), with $D = 14$ in. (34.3 cm); tread and pitch varied accordingly. Step frequency was fixed at $f = 50$ steps/min, based on the standard practice of using constant frequencies, and on Templer's (1975) empirical equation showing that step frequency is approximately constant in free climbing over this range of stairway conditions (see Warren, 1983, for a discussion). Identical values of D and f for the two groups introduced slight violations of geometric and kinematic similarity, which will be considered in this experiment's *Discussion*.

Gas samples were collected in a Douglas bag mounted at head level, the climber breathing through a rubber mouthpiece with a modified two-way Otis-McKerrow valve. The volume of expired air was measured with a Precision wet-test meter, and O_2 and CO_2 analyses were performed with a Beckman E-2 oxygen analyzer equipped with Drierite and soda-lime circuits. Ambient temperature and pressure were monitored with a Welch thermometer/barometer. The rate of oxygen uptake (liters/min STPD) was calculated by computer and converted to rate of energy expenditure (kcal/min) by multiplying by 4.825, the caloric equivalent for a mixed fat and carbohydrate metabolism.

Procedure. Testing involved daily 1-hr sessions for 19 consecutive weekdays. The first was a practice session; then participants received two test trials per session for the remainder of the experiment. The six stairway conditions were run in a random order, with six consecutive test trials in each condition.

The tests employed a steady-state collection method. A test session consisted of a 20-min rest period followed by a 5-min exercise bout, including 4 min of warm-up exercise and a 1-min sample of expired air. After another 20-min rest period, a second test trial was run. Pilot tests had indicated that a metabolic steady-state was reached within 2–4 min of exercise in all experimental conditions. It had also been determined that a step frequency of 50 allowed an aerobic metabolism to be maintained in the most strenuous ($R = 10$ in.) condition, ensuring that oxygen uptake would accurately reflect total energy expenditure. A check was provided by monitoring the ventilatory equivalent (ratio of expired air to oxygen consumed), which remained within a range of 19.4 to 26.7 for all participants, indicating that an aerobic metabolism was maintained in all trials.

Participants wore gym clothes and tennis shoes and did not eat, exercise, or drink coffee, alcohol, or dairy products for 2 hr prior to testing. They were instructed to climb normally without touching the stairmill handrails. Body weight without shoes was measured in each session on a balance scale.

Results

Metabolic rate is plotted as a function of riser height in Figure 7. Each data point represents the mean of six trials for each participant.⁵ In accordance with accepted assumptions for the analysis of energetic data (see Ralston, 1976), the data for each group

were fit with a quadratic equation by least-squares multiple regression, and the resulting curves are also shown in Figure 7. The regression equation for the Short group is

$$E_t = 1.785R^2 - 10.680R + 106.420, \quad (14)$$

where E_t is cal/kg-min and R is riser height in inches. This equation fit the data with a multiple correlation of $R = .994$, and an F test was significant, $F(2, 12) = 501.95$, $p < .001$. For the Tall group the regression equation is

$$E_t = .550R^2 + 5.395R + 49.870, \quad (15)$$

with a correlation of $R = .992$, $F(2, 15) = 461.168$, $p < .001$.

The data were transformed to energy expenditure per vertical meter (dividing E_t by f and multiplying by the number of risers per meter), and the fitting equations and group means are replotted in Figure 8. The resulting values were comparable to those found in other studies under similar conditions of continuous ascent.⁶ A two-way repeated measures analysis of variance (Riser Height \times Group) was performed on the transformed data,⁷ yielding a significant main effect of riser height, $F(5, 20) = 57.87$, $p < .001$, a significant group effect, $F(1, 4) = 14.44$, $p < .05$, and a significant interaction, $F(5, 20) = 5.22$, $p < .01$.

To locate the minimum of each function, the transformed fitting equations were differentiated, set equal to zero, and solved for R .

⁵ To eliminate a potential source of error, data from the Short group in the 10-in. condition were excluded from the analysis. In this extreme position the limit of the tread mechanism was surpassed, resulting in springlike, slightly rocking treads that could aid the ascent of lightweight climbers. Force-displacement tests indicated that the heavy Tall climbers hit bottom on the rocking treads but that the lighter Short climbers did not and thus could take advantage of a springboard effect.

⁶ For example, in the 8-in. condition, energy expenditure was 13.4 cal/kg-m for the Short group and 12.6 cal/kg-m for the Tall group. Richardson (1966) obtained 13.3 cal/kg-m (with $R = 7.76$ in.; $D = 13.3$ in. [33.78 cm]; $f = 62$), and Benedict and Parmenter (1928) found 11.9 cal/kg-m (with $R = 8.3$ in. [21.08 cm], $D = 13.8$ in., $f = 45$) both with female subjects.

⁷ The missing data points in the Short 10-in. condition were replaced with values from individual fitting equations for the analysis of variance.

This yielded optimal riser heights of 7.72 in. (19.61 cm, 13.295 cal/kg-m) for the Short group and 9.52 in. (24.18 cm, 12.501 cal/kg-m) for the Tall group.

To examine the similarity hypothesis, the group curves are replotted on intrinsic axes in Figure 9, where the ordinate is the ratio of total energy expended in one step cycle divided by vertical work performed in that step cycle, a measure of the inverse of ecological efficiency (Warren, 1983). This renders the curves nearly parallel and vertically aligned, although not congruent, indicating

that, under the experimental conditions, Tall climbers are more efficient overall than Short climbers. Expressing the optimal riser heights intrinsically yields

$$R_o/L = 19.61 \text{ cm}/74.50 \text{ cm} = .26 \quad (16)$$

for the Short group and

$$R_o/L = 24.18 \text{ cm}/93.97 \text{ cm} = .26 \quad (17)$$

for the Tall group. The optimal ratio for each participant, based on individual fitting curves, is given in Table 2.

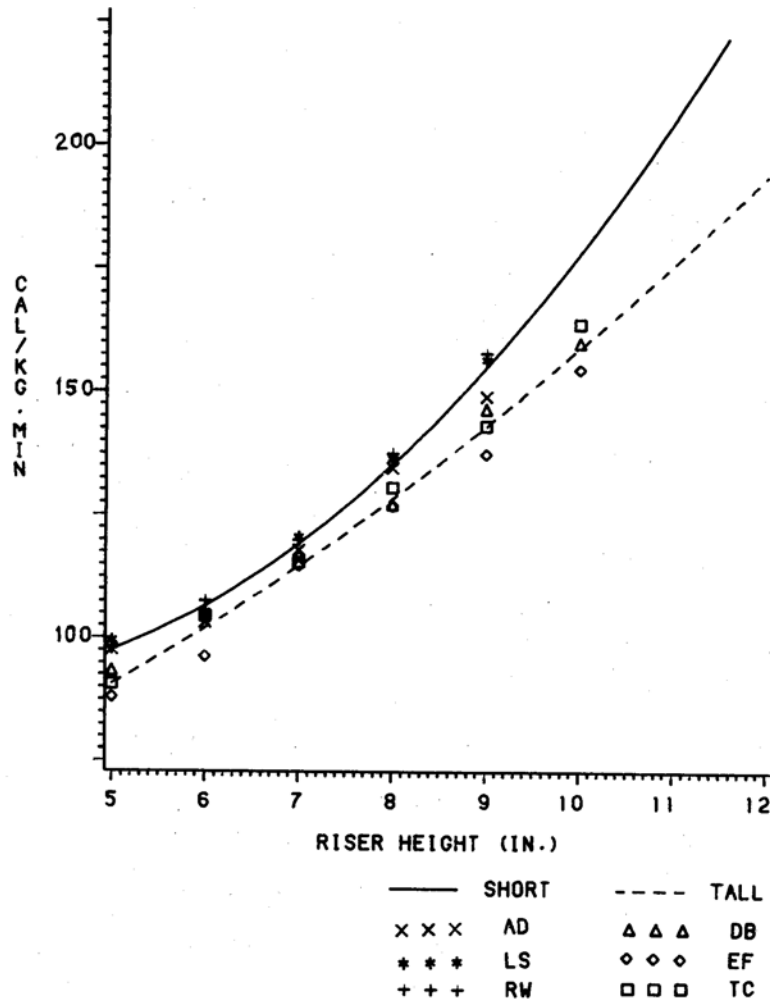


Figure 7. Rate of energy expenditure (in calories per kilogram of body weight per minute) as a function of riser height for each subject. (Solid symbols represent Short subjects; hollow symbols represent Tall subjects. The curves are fit to each group's data.)

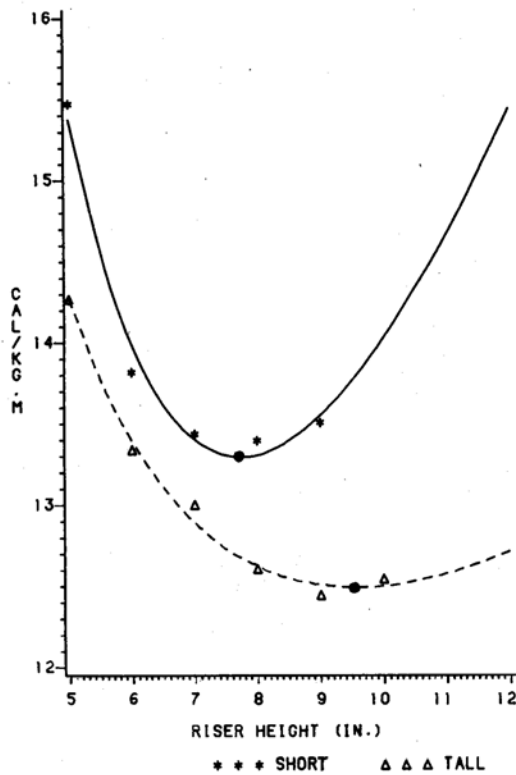


Figure 8. Mean energy expenditure (in calories per kilogram of body weight per vertical meter) as a function of riser height for each group. (The data and fitting curves are transformed from Figure 7. Minima are indicated by solid circles.)

Discussion

The results indicate that the riser height requiring minimum energy expenditure is just over one quarter of leg length for both short and tall climbers. This finding is taken as evidence of an optimal point in the climber-stair system:

$$R_o/L = .26. \quad (18)$$

This value is close to the optimal ratio of $R_o/L = .25$ determined from Benedict and Parmenter's (1928) data for women climbers. The result also supports the similarity hypothesis that the optimal point is a constant over scale changes in the system.

Optimal riser heights of 7.7 in. to 9.5 in. (19.5 cm–24.1 cm) are considerably higher than those found in common stairways, which

are based on biomechanically questionable standards and other architectural considerations. The data help explain the oft-noted complaints about monument steps, with their 5-in. to 6-in. risers and deep treads, reiterated by many participants in the present study. Architects have long employed monument steps in the belief that a gentler slope is easier to climb and that it is aesthetically pleasing, providing an imposing visual pedestal for major buildings. But as is apparent in Figure 8, far from making long flights of steps easier to climb, low risers increase total energy expenditure by 15%, and deep treads often make an efficient stride length impossible as well. This suggests that part of the aggrandizing effect of monument steps may derive from increasing the actual "energetic" distance to the summit.

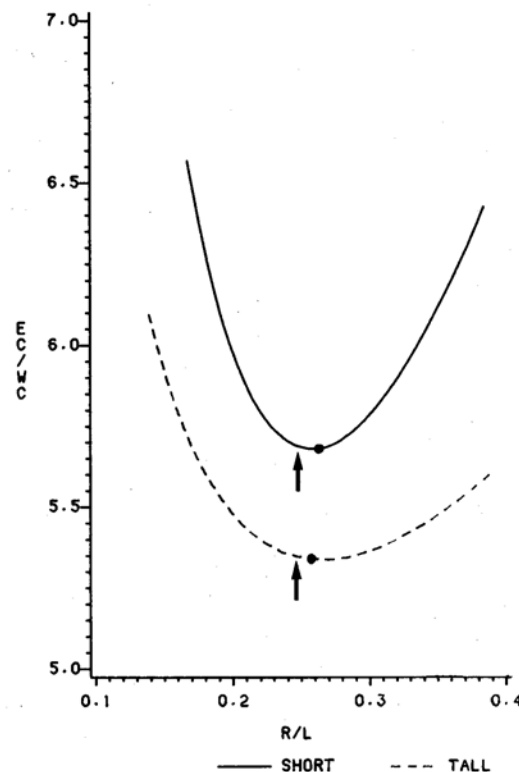


Figure 9. Intrinsic plot: inverse efficiency (energy expended per step cycle/work done per step cycle) as a function of R/L . (The fitting curves are transformed from Figure 8. Minima are indicated by solid circles; the arrows indicate visual riser preference as determined in Experiment 3.)

These findings argue for the replacement of standard monument steps with an ergonomically sound design, incorporating higher risers and shallower treads. Revised architectural guidelines should be based on further research with both women and men during descent as well as ascent; they must also take into account the problems faced by children, the elderly, and the handicapped in climbing high risers (Corlett et al., 1972). Considering the present results for ascent, a tentative design recommendation for the general population would be a riser height of approximately 7 in. (17.8 cm), with a stair diagonal of 14 in. (35.6 cm).

The statistically significant difference in overall efficiency between the Short and Tall groups could be accounted for by slight violations of similarity in the experimental conditions. First, for true geometric similarity, stair diagonal D should not have been held constant at 14 in. but varied as a proportion of leg length (as in Equation 5). It is known, for example, that preferred stride length in level walking varies directly with leg length (Dean, 1965; DuChatinier, Molen, & Rozendol, 1970; Murray, Drought, & Kory, 1964), and the same should hold true for stair climbing. This would have yielded a D 3 in. smaller for the Short group. Thus, enforced overstriding by Short participants could have reduced their efficiency in all conditions. Second, holding step frequency constant at 50 steps/min for both groups introduced a violation of kinematic similarity (Gunther, 1975). Treating the swinging leg as a simple pendulum, its natural frequency (requiring minimum energy expenditure) would have been higher for the Short participants than for Tall participants; such a tendency for preferred step frequency to vary inversely with leg length has been observed in level walking (Booyens & Keatinge, 1957; Dean, 1965; DuChatinier et al., 1970; Workman & Armstrong, 1963). Thus, the experiment's relatively slow step frequency could have reduced the efficiency of the Short group more than that of the Tall group. If these two factors were equated, the overall group difference in efficiency should be eliminated.

Now that an optimal point in the climber-stair system has been identified, it can be used to predict perceptual preferences.

Table 3
Anthropometric Data for Participants in Experiment 3

Group	Height	Eyeheight	Leg	L. leg
Short				
<i>M</i>	164.52	153.80	76.98	43.85
<i>SD</i>	4.00	3.54	2.97	2.05
Tall				
<i>M</i>	190.65	180.13	92.99	51.38
<i>SD</i>	4.29	3.86	3.53	1.99

Note. L. leg = lower leg length. Measurements are in cm.
 $N = 12$ per group.

Experiment 3: Visual Perception of Optimal Riser Height

Experiment 2 determined that the energetically optimal ratio of riser height to leg length is .26 for both short and tall climbers. The present experiment examined the hypothesis that the perceptual preference for riser height, symbolized R_o^*/L , corresponds to this optimal point. Slides of stairways with risers varying from 5 in. to 10 in. (12.7 cm–25.4 cm) were presented to short and tall observers, and preference judgments were obtained in both forced choice and rating tasks.

Method

Subjects. Two groups of 12 male college students were paid to participate in the experiment, the Short group having a mean height of 5 ft 4.8 in. (164.5 cm) and the Tall group having a mean height of 6 ft 3.1 in. (190.7 cm). Anthropometric data are presented in Table 3.

Displays. For the choice task, black-and-white slides were taken of two adjustable wooden stairways standing side by side. The six stairway conditions were the same as in Experiment 2, with riser height varying from 5 in. to 10 in. (12.7 cm to 25.4 cm) and stride fixed at 14 in. (35.6 cm). To equate the vertical work specified for climbing, the number of steps in each stairway was set so that total height was as close as possible to 40 in. (101.6 cm). A box was centered above the top steps at a height of 80 in. (203.2 cm). The stairways were placed with their bottom steps aligned, and risers and treads were painted white. No reference objects appeared in the slides, but a single stair from the shortest (5 in., 12.7 cm) and tallest (10 in., 25.4 cm) conditions was present on the floor of the testing room below the projected image. Because of the duration of the experiment, participants remained seated to avoid fatigue that might influence their judgments. Otherwise, photographic and projection conditions were the same as in Experiment 1. All possible nonidentical pairs of stairways were photo-

graphed in each left-right position, for a total of 30 slides.

For the rating task, slides were identical except that only one stairway appeared in each. Total stairway height was as close as possible to 40 in. (101.6 cm) and the box was centered above the top step.

Procedure. All participants received the choice task first and the rating task second, each preceded by a set of instructions. For the choice task, slides were arranged in a random order and presented once in each direction, for a total of 60 trials. The test sequence was preceded by two practice trials, first a 5-in.-10-in. (12.7 cm-25.4 cm) pair, and then a 7-in.-8-in. (17.8 cm-20.3 cm) pair. Participants were told to think about "stairs that are either too high for you, so that each step requires a lot of effort, or too short for you, so that you spend a lot of effort taking many steps but getting nowhere." They were then instructed to indicate on an answer sheet which of the two stairways would be "more comfortable for you to climb to the top" in order to put a tennis ball in the box, climbing one step at a time at a comfortable speed. It was explicitly stated that the stairways always went up to the same total height, and the two steps in the testing room were identified as the endpoints of the test series, corresponding to the stairways in the first practice slide.

For the rating task, slides of the six stairways were presented in a random order for a total of 60 trials, preceded by two practice slides (5 in. and 10 in., 12.7 cm and 25.4 cm) which were identified as the endpoints of the test series. Participants were told that they would be seeing the same set of stairways again, one at a time. They were instructed to rate each stairway on a scale of 1 to 7, with 1 corresponding to a *poor, uncomfortable* stairway and 7 a *good, comfortable* stairway to climb to the top. In both tasks, test slides were presented for approximately 8 s, and the experiment lasted about 30 min.

The one factor that could not be controlled in the perceptual tasks was the observer's potential step frequency, which could affect judgments of preferred riser height. However, pilot data on energy expenditure by one subject indicated that optimal riser height was the same when determined at frequencies of 30, 50, and 70 steps/min (Warren, 1983). Thus, optimal riser height appears to be independent of step frequency, and leaving frequency unspecified in the perceptual tasks should not have affected judgments of preferred riser height.

Results

Choice task. The percentage of trials in which each riser was chosen is presented in Figure 10, which shows the Tall group curve shifted to the right of the Short group curve. A two-way repeated measures analysis of variance (Riser Height \times Group) was performed on individual scores, with a significant main effect of riser height, $F(5, 110) = 447.00$, $p < .001$, no main group effect, because the two U-shaped curves cover the same range of scores, $F(1, 22) = 0.63$, $p > .05$, but a signif-

icant interaction, $F(5, 110) = 341.59$, $p < .001$. Due to the coarseness of the riser series, a more precise estimate of preferred riser height for each group was obtained by calculating the average of each participant's most frequently chosen riser, yielding means of 7.42 in. (18.85 cm, $SD = 1.31$ cm) for the Short group and 9.00 in. (22.86 cm, $SD = 1.95$ cm) for the Tall group.

The choice data are plotted on an intrinsic R/L axis in Figure 11. The resulting curves are nearly congruent, eliminating the group difference. When preferred riser height is expressed intrinsically, the results are

$$R_o^*/L = 18.85 \text{ cm}/76.98 \text{ cm} = .25 \quad (19)$$

for the Short group, and

$$R_o^*/L = 22.86/92.99 \text{ cm} = .25 \quad (20)$$

for the Tall group. These values are close to the optimal ratio of .26 obtained in Experi-

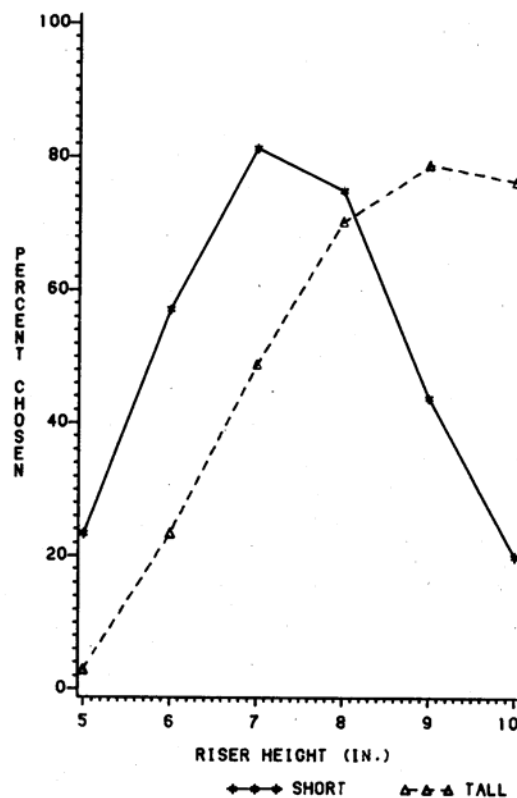


Figure 10. Mean percentage chosen as a function of riser height for each group.

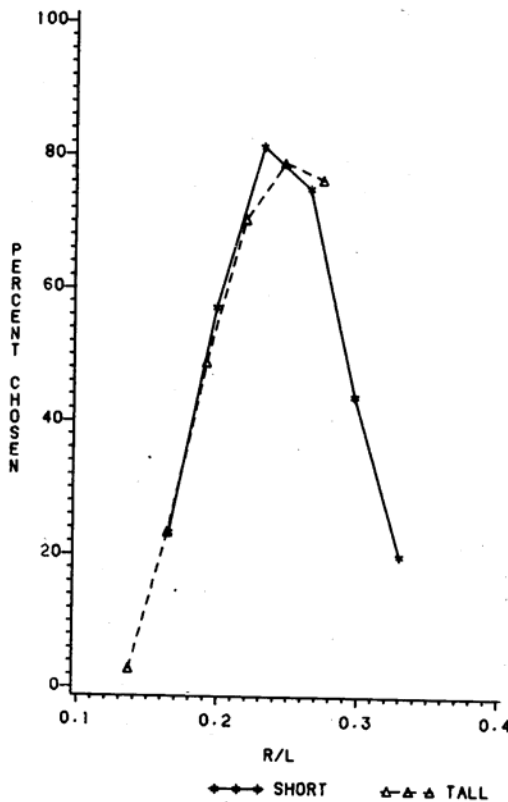


Figure 11. Intrinsic plot: mean percentage chosen as a function of R/L for each group.

ment 2 (Equations 16 and 17; see arrows in Figure 9).

Rating task. Mean ratings are plotted in Figure 12 for each group. As with the choice data, the Tall curve is shifted to the right of the Short curve. A two-way repeated measures analysis of variance on individual ratings yielded a significant main effect of riser height, $F(5, 110) = 33.76$, $p < .001$, a significant group effect, apparently due to the asymmetry of the Tall group curve, $F(1, 22) = 6.42$, $p < .01$, and a significant interaction, $F(5, 110) = 27.19$, $p < .001$. A precise estimate of preferred riser height was obtained by averaging each participant's highest-rated riser, yielding means of 7.25 in. (18.42 cm, $SD = 1.91$ cm) for the Short group and 8.46 in. (21.49 cm, $SD = 2.39$) for the Tall group. Although more variable and slightly lower, these values are reasonably close to those obtained in the choice task.

When the rating data are plotted on an intrinsic R/L axis in Figure 13, the group curves again appear nearly congruent. Expressing preferred riser height intrinsically,

$$R_o^*/L = 18.42 \text{ cm}/76.98 \text{ cm} = .24 \quad (21)$$

for the Short group, and

$$R_o^*/L = 21.49 \text{ cm}/92.99 \text{ cm} = .23 \quad (22)$$

for the Tall group. These ratios are slightly lower than those obtained in the choice task (Equations 19 and 20).

Discussion

The results of the choice task indicate that both short and tall observers visually prefer a riser height that is one quarter of their leg length, in order to climb through a given

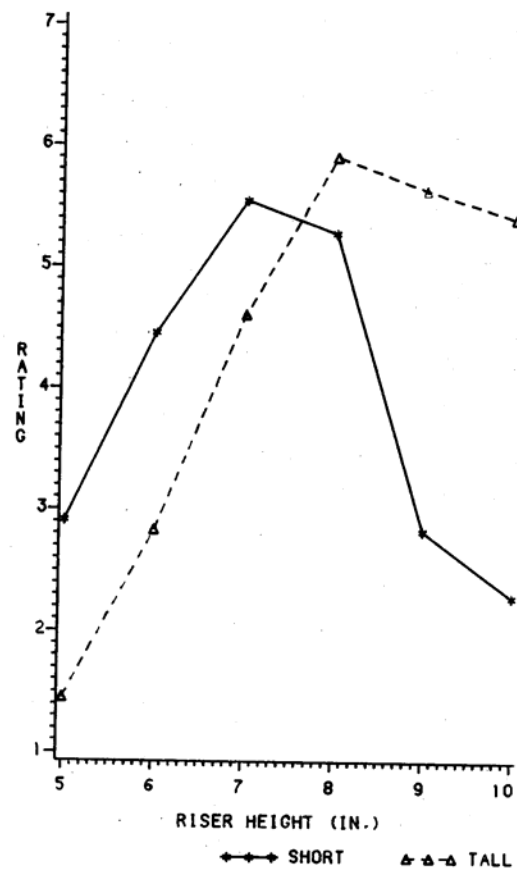


Figure 12. Mean ratings of "climbability" as a function of riser height for each group.

vertical distance. This value closely matches the energetically optimal ratio of $R_o/L = .26$ established in Experiment 2, lending support to the hypothesis that optimal points predict perceptual preferences and to the similarity hypothesis that these values are constant over scale changes in the system.

Converging evidence is provided by the rating task, although ratings of preferred riser height were somewhat more conservative and more variable across participants. This difference may be due to the relative insensitivity or more cognitive nature of the rating task when compared with forced choice. Nevertheless, the rating results are reasonably close to the choice results, and a general optimal π value for perception and action in stair climbing appears to be justified, approximately

$$\pi_o = .25. \quad (23)$$

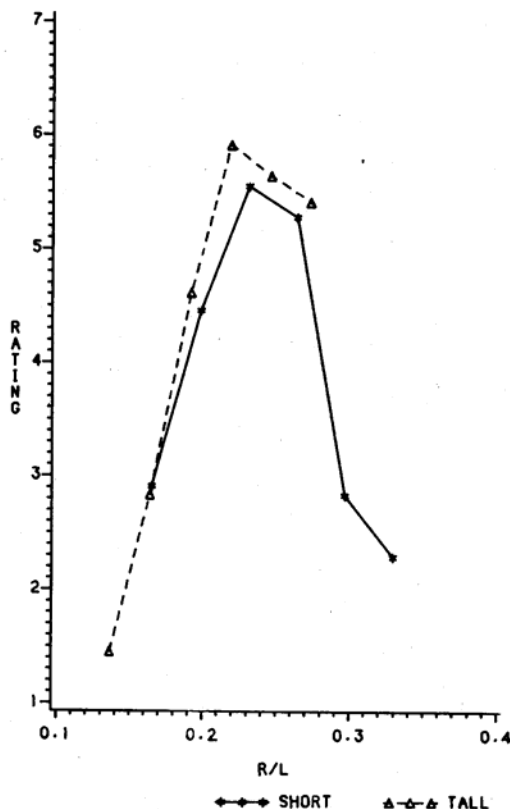


Figure 13. Intrinsic plot: mean ratings of "climbability" as a function of R/L for each group.

It is important to note that the visually preferred risers, although closely matching the energetic minima for both groups, are considerably higher than those found in ordinary stairways. This indicates that subjects do not simply prefer what is familiar, as a result of years of experience with normal stairways, and argues in favor of the hypothesis that perceptual preferences are related to the energetics of action. The difference in preferred riser height between the two groups also supports this assessment, because both short and tall subjects have had experience with the same range of common stairways.

The results indicate that an interpretation of optimal, or best fit, affordances in terms of energetics is relevant to visual perception and predicts visual preferences. In selecting a path of locomotion, an actor must in some sense be perceiving "the work to be done" on various routes to achieve a particular goal. For example, there is evidence in the literature on optimal foraging that many species perform visually guided behavior sequences that are energetically efficient (Pyke, Pulliam, & Charnov, 1977; Zach & Smith, 1981). This is not to suggest that an animal computes its own metabolic efficiency for each potential route, but rather that there must be intrinsic optical information specific to paths of least work. The actor could thereby perceive the best energetic fit between itself and the environment to guide a particular activity.

General Discussion

The experiments provide evidence that functional perceptual categories and preferences correspond to critical and optimal points in an animal-environment system. First, the visual category boundary between climbable and unclimbable stairs was predicted by a biomechanical model of critical riser height, yielding a critical ratio of $\pi_c = .88$. Second, visually preferred riser height was predicted by the energetically optimal riser, yielding an optimal ratio of approximately $\pi_o = .25$. Finally, these values were constants across short and tall participants, as predicted by the similarity hypothesis, suggesting that intrinsically determined crit-

ical and optimal points are scale independent. The effects of adopting natural or intrinsic units of measurement are underscored by the near congruence of group curves when plotted on intrinsic axes, thereby "annihilating" group differences and rendering them functionally equivalent (cf. Rosen, 1978a, 1978b).

These results support the proposition that observers are capable of perceiving affordances, including their critical and optimal points. If this is so, it represents a step toward answering the question of how animals visually guide their activities in a cluttered environment. By perceiving environmental objects in relation to their action capabilities, animals can detect the possible and most economical courses of action in a given situation and can even act to alter the situation adaptively.

One possible account of this ability is that environmental dimensions and body dimensions are perceived and represented independently, in units of some extrinsic or absolute metric. These two separate sets of measures would then have to be calibrated and critical and optimal values computed on the basis of prior experience. Alternatively, a body-scaled or action-scaled metric could be adopted for the analysis of visual information and perceptual-motor performance. The perception of affordances would be based on intrinsic optical information for the relationship between environmental properties and properties of the observer's own action system, such as the ratio R/L . The advantages of this latter approach are twofold: First, intrinsic optical information is available to observers under natural viewing conditions, whereas the existence of absolute information is problematic; second, intrinsic information is directly relevant to the control of action, without computation or the calibration of extrinsic metrics. This approach yields a simpler model that has the potential to account for the high degree of accuracy in perceptual performance.

In the present case, the successful guidance of stair climbing could be accomplished with optical information about the relationship of riser height to leg length or to some other related body dimension such as standing eye height ($R/L = .51 R/e$ in the present sample). It can be demonstrated that, under natural viewing conditions, both static and optical

flow information exist to specify the height of any object as a ratio of eye height (Lee, 1980; Sedgwick, 1973, 1980; Warren, 1983). Particular *margin values* of such an optical variable specify the critical and optimal points of R/L , and could be exploited for the control of climbing. In the case of behavior requiring the perception of time to contact with a surface, for example, margin values of the inverse of the rate of optical expansion (which specifies time to contact for motion of constant velocity) have been found for the initiation of wing-folding in diving water birds (Lee & Reddish, 1981), landing deceleration in houseflies (Wagner, 1982), muscle activity during falls in humans (Dietz & Noth, 1978), and arm extension when hitting an approaching ball (Lee, Young, Reddish, Lough, & Clayton, 1983).

Although the origin of such margin values is uncertain, one possibility is that they are indexed for a perceiver by the qualitative features of system dynamics during exploratory activity. Thus, the energy minima illustrated in Figure 9 could act to "point out" the optical margin value that corresponds to optimal riser height. Action-scaled information for affordances is most likely based on such a complex of ecological relations (see Kugler & Turvey, in press). It remains for further research to determine whether the available eyeheight information is actually utilized by human climbers.

The principles of intrinsic measurement and the dynamics of critical and optimal points are general and can be applied to other affordances and related problems such as the design of architectural environments (e.g., Panero & Zelnik, 1979). The material and informational bases for such activities as reaching, grasping, lifting, sitting, passing through apertures, stepping down ledges, jumping gaps, locomotion over surfaces with varying properties, foraging and food selection, predation, and so on are amenable to such an analysis. By anchoring perception in the biomechanics and energetics of action, this approach seeks a natural basis for the many categorical distinctions and preferences made in the course of ordinary activity, and, conversely, seeks a lawful explanation for the successful visual control of action.

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Received January 25, 1984

Revision received April 23, 1984 ■