Psychophysical Assessment of Toddlers’ Ability to Cope With Slopes

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This research examined how infants in early stages of walking determine whether a hill is safe or risky for locomotion. A psychophysical staircase procedure provided estimates of infants’ physical ability to walk up and down slopes (2° to 36°), and a “go ratio” indexed the accuracy of their perceptual judgments. On average, perceptual judgments were scaled to walking ability on slopes. Children walked on safe slopes and balked on risky ones. For ascent, perceptual judgments were related to length of walking experience and walking skill on flat ground. Better walkers were also better perceivers. For descent, judgments nearly mirrored exploratory activity. Better perceivers explored hills more efficiently by hesitating, touching, and testing different positions on hills around the limits of their physical ability.

Adaptive movement requires prospective control—the ability to plan actions ahead of time on the basis of information obtained from exploratory movements (Lee, 1994). Previous research indicates that adults are expert at navigating everyday situations. They judge correctly whether stairs are too high for walking upright (Mark, 1987; Mark & Vogele, 1987; Warren, 1984), chairs are too high for sitting comfortably (Mark, Baillet, Craver, Douglas, & Fox, 1990), doorways are too narrow to pass through forward (Warren & Whang, 1987), or objects are too distant to reach (Carello, Grososký, Reichel, Solomon, & Turvey, 1989). For such well-practiced actions, adults perceive what actions are possible on the basis of brief exploratory glances involving slight movements of their eyes, head, and body.

However, adults fare less well when unaccustomed tasks require new exploratory strategies. For example, when adults’ body dimensions were altered by wearing platform shoes, they needed to make more exploratory movements to judge appropriate chair heights for sitting (Mark et al., 1990). If participants could take a few steps in their new shoes, sway slightly from side to side, and move their heads, they quickly recalibrated chair heights appropriate for their elongated bodies. If exploratory movements of head and body were reduced by looking through a peephole, judgments were poor. If forced to stand in an awkward pose (heels together, toes out), participants moved quite a lot to maintain balance, but their judgments were poor. Findings indicate that exploratory stepping and swaying movements yielded information about altered body dimensions and their relevance for sitting, and that adults knew how to explore when they were allowed to stand in a customary position but not when they were in an awkward pose.

Like the adults wearing platform shoes and standing in an unaccustomed pose, when infants first begin to walk they must often find themselves perched in new and clumsy positions, with their attention focused on the immediate exigencies of maintaining balance. This research addresses how infants guide action adaptively within a developmental context of rapidly changing body dimensions, new skills, and increasing experience. I examined the origins of prospective control of locomotion by testing young walking infants in a novel situation—going up and down steep and shallow hills. The central questions of interest were whether infants of various sizes, degrees of locomotor skill, and experience know when a hill provides safe going or danger from falling, and what exploratory strategies infants use to determine the difference.

Affordances of Slopes

Prospective control of locomotion relates to the concept of affordances (J. J. Gibson, 1979). An affordance is a relationship or “fit” between two sets of conditions—the current status of actors’ bodies and skills and the material properties of the environmental situation. Very simply, it refers to the physical requirements for an action. For example, walking uphill requires a fit between current capabili-
ties (strength, balance, flexibility, endurance, etc.) and features of the slope (surface slant, frictional properties, size of the hill, etc.). Change in capabilities can augment or constrain possibilities for action. The same hill can be too steep for novice walkers but easily managed when infants develop more strength and postural control. Reciprocally, change along an environmental dimension will eventually force a transition from one action to another. Continued increases in surface slant will eventually require a switch from walking upright to climbing on all fours. At any given point in time, walking is either feasible or not, regardless of whether we brave the hill or choose an alternate route.

Describing an affordance is difficult. For example, walking uphill and walking downhill have different biomechanical constraints and tax different capabilities. Walking uphill is more tiring but easier to control. We expend a lot of energy hoisting our legs upward (Dean, 1965), but gravity constrains forward momentum from step to step. The supporting leg straightens completely, so that muscles contract to exert force. The moving leg contacts the hill in a flexed position partway through its swing cycle, and its placement is not critical for keeping balance. In case of mishaps, hands are well-positioned to break a fall so that the practical consequences of falling while walking uphill are minimal (Adolph, Eppler, & Gibson, 1993a).

In contrast, walking downhill is less wearing (Dean, 1965) but more difficult to control (Nelson & Osterhoudt, 1971). We must curb forward momentum either by taking small, slow steps and bracing between them or by running down the hill and braking on flat ground at the bottom (McGraw, 1935). The supporting leg is in a bent position so that muscles must lengthen (a harder job) to exert force. The moving leg straightens at the end of its swing cycle before contacting the slope, and its placement is critical for keeping balance. Hands are ill-positioned to break a fall, and the consequences of falling while walking downhill can be quite serious.

Performance differences between ascent and descent begin early in life and continue throughout childhood. In her meticulous description of one baby's daily progress on slopes (11° to 70°), McGraw (1935) observed that the child mastered going up each hill several weeks before he managed descent. For example, he walked up 32° at 13 months but did not walk down the same hill until 2 months later. Without a daily training regime, most infants have little experience with slopes, and their achievements are more modest. Adolph et al. (1993a) tested crawling (8.5 months) and walking (14 months) infants on a walkway slanting at 10°, 20°, 30°, and 40°. Parents at the far end of the walkway urged their babies to come up and down each hill presented in increasing increments, for a total of eight trials. Infants in both groups managed steeper hills going up than going down using their typical method of locomotion. Preschool children showed the same pattern of results in more demanding beam-walking tasks (Adolph, Ruff, Kim, & Capozzoli, 1994; Giacalone & Rarick, 1985). Children walked faster and farther along upward-slanting beams than along level or downward-slanting beams. Variations in the height and width of beams most disrupted performance during descent.

Exploring Affordances for Locomotion

According to J. J. Gibson (1979), perception of affordances is the basis for prospective control. Information for guiding future activity can be discovered on the basis of current movements, so that exploration and performance normally weave together seamlessly. The task is more difficult during infancy when situations are novel and bodies and skills change dramatically. Infants must learn to perceive what they can do next as they struggle to maintain control over what they are doing in the present moment. Generation and refinement of various types of exploratory activity appear to be key elements of the learning process (E. J. Gibson, 1969, 1988, 1991).

For example, there are three potential strategies that infants could use to obtain information about affordances for walking over slopes. The most direct way, of course, is to try to walk and observe the consequences. Such learning by doing would be a sensible strategy for going up hills but not for going down, where mishaps can be serious. In the experiment by Adolph et al. (1993a), for example, nearly every baby charged up every hill without hesitating or touching slopes from the starting platform. Although falls were common during ascent, babies safely caught themselves without incident.

A more prudent exploratory strategy is to cautiously probe the surface by careful looking or touching (E. J. Gibson et al., 1987). Information for surface slant, frictional properties, the dimensions of the hill, and one’s own postural stability may be specified visually, as infants peer over the edge and generate motion parallax. Haptic–proprioceptive information may be obtained by prodding and rubbing the hill with hands or feet. Adults can use visual exploration and exploratory movements of their feet to detect affordances for walking up hills. Kinsella-Shaw, Shaw, and Turvey (1992) found that adults judged correctly when a large visible ramp was the same slant as a small hidden ramp they felt with a foot, and judgments of whether they could walk up hills closely matched their actual abilities. Adolph et al. (1993a) found that infants spontaneously use cautious probes to detect affordances of slopes but only on downhill trials. After touching, most toddlers walked down shallow hills and slid safely down steep ones. Crawlers, in contrast, used information from cautious probes less efficiently. They stopped, looked, and touched steep slopes, but many plunged down headfirst nonetheless. Walking infants also detect affordances on the basis of slant alone when height and surface texture of hills are held constant (Weiner & Adolph, 1993), and they detect affordances on the basis of texture alone when slant and height are held constant (Adolph, Eppler, & Gibson, 1993b).

Adolph and colleagues (1993a) observed a third type of exploratory activity, used exclusively by walking infants and only during descent. Similar to the means–ends exploration described by Piaget and others in object tasks (e.g.,
Willats, 1989), toddlers explored alternative means of descent by testing different sliding positions on the starting platform. Most of the toddlers discovered an appropriate method to slide safely down.

**Perceptual Judgments, Exploration, and Individual Differences**

Overall, previous findings suggest that young walking infants use different exploratory strategies and have some cognizance of the different demands of walking up and down safe and risky hills (Adolph et al., 1993a). However, with only one trial at each of four increments of slant in the previous work, it was not possible to determine infants' actual ability to walk over slopes or to examine factors that led to individual differences in infants' success.

The present experiment aimed to assess infants' perception of affordances more precisely. As before, the overall plan was to encourage new walkers to go up and down steep and shallow hills, so as to observe exploratory behavior on the starting platform and success at navigating the slopes. I used a psychophysical staircasing procedure to estimate the steepest hill each child could walk up and down without falling— their "walking boundaries"—and a "go ratio" to assess the accuracy of children's perceptual judgments. With the new procedure, I could test whether children underestimate their ability, walking on hills where they have a reasonable probability of success, or overestimate their ability, trying to walk on hills where they are likely to fall. Of special interest was children's exploratory activity before going onto slopes. Most children had little practice walking over steep hills, so presumably they must discover information for affordances during the experimental session. If toddlers know how and when to explore, then this should be reflected in the accuracy of their perceptual judgments. I reasoned that more efficient explorers should be more accurate perceivers.

I also examined three additional sources of individual differences in ability to cope with slopes. The interrelated variables of locomotor experience, walking skill on flat ground, and body proportions are likely to be related to walking boundaries on slopes, providing independent validation of the staircase procedure. Walking skill is positively correlated with length of walking experience (e.g., Bril & Brieniere, 1992; Burnett & Johnson, 1971), and children with less babyish proportions tend to walk sooner and walk better than more top-heavy children (e.g., Shirley, 1931; Thelen, 1984). Kinematic measures of walking skill on flat ground are especially promising predictors because the measures are more reliable than parents' reports of locomotor experience (Walk, 1966) and there is a wider range in skill than in body proportions at 14 months (Shirley, 1931).

Moreover, these factors may point to underlying processes in perception of affordances. For example, children with more days of walking experience may have had more opportunities for learning in relevant situations such as stairs, playground slides, or a bad fall. Along similar lines, several studies found positive correlations between length of crawling experience and avoidance on a visual cliff (e.g., Bertenthal & Campos, 1984; Campos, Bertenthal, & Kermoian, 1992; Richards & Rader, 1981, 1983). More skillful walkers on flat ground may attend to and use information that goes unnoticed by more tipsy toddlers, especially information for controlling balance during single-leg support (see Bril & Brieniere, 1992; Schmuckler & Gibson, 1989). The same sorts of information may generalize from flat ground to slope as children walk over the starting platform toward the hill. Last, it is possible that children use information about their body proportions to determine whether slopes are safe for walking. Several experiments with older children and adults found that perception of affordances was scaled to body dimensions (e.g., Pufall & Dunbar, 1992; Warren, 1984), although no one has yet found such results with infants or toddlers.

In sum, the purpose of this experiment was to determine the steepest hills each child could walk up and down and to measure the accuracy of perceptual judgments and the efficiency of exploratory activity relative to infants' actual ability. I extended previous results with a new procedure for estimating walking boundaries on hills. Children received many more trials on a walkway with smaller increments of slant than in the earlier studies, and I varied slope order to control for order effects. I obtained measures of children's locomotor experience, walking skill on flat ground, and body proportions to determine whether independent contributions of each variable could account for individual differences in ability to cope with slopes.

**Method**

**Participants**

Thirty-one toddlers (17 boys and 14 girls) were recruited from published birth announcements. Most children were White, middle class, and lived in a university area. All children were within a 2-week span of their 14-month birthday ($M = 13.99$ months, $SD = 0.19$ months) and could walk at least 10 feet independently. They wore diapers and rubber-soled shoes during the test session. Three additional girls became fussy and did not complete testing. Families received souvenir photographs and certificates for their participation.

Parents provided information about children's locomotor experience, including when they began crawling and walking, experience on playground slides and stairs, and serious falls while moving around on their own. Parents referred to baby diaries or calendars when available.

**Sloping Walkway**

Children encountered different affordances for locomotion on a wooden walkway with adjustable slope (Figure 1). All could walk safely over the shallowest slopes but none over the steepest ones. The walkway had three sections connected by dowel hinges. There were flat sections at each end (83.6 cm wide × 76.75 cm long × 4.3 cm thick) that served as starting and landing platforms and a sloping section in the middle (79.5 × 91.0 × 4.3 cm). One end segment rested on a stationary platform 71 cm high so that the total height was 75.3 cm. The other end rested on a hydraulic pump that
standing at one end of the walkway. Parents at the other end encouraged them to come up or down to get dry cereal or a toy while an experimenter followed alongside to ensure their safety. If the children did not start onto a hill within 60 s or if they became extremely fussy, the experimenter ended the trial.

The experimenter used a modified psychophysical staircase procedure (Cornsweet, 1962) to estimate the steepest hills children could walk up and down—their walking boundaries. The experimenter scored each trial online as success, S (walked safely), failure, F (tried to walk but fell), or refusal to walk, R (slid, climbed on all fours, or avoided going). The staircase procedure is similar to Piaget’s (1961) concentric clinical method, where “step” size (increment of stimulus) depends on the outcome of the previous trial, and most trials occur at increments where behavior is most variable (Gibson & Olum, 1960). A general rule of thumb is to present stimuli in increasing increments until a change in response, then decreasing increments until a return to the baseline response, then increasing increments until another change, and so on until reaching a predetermined criterion (Cornsweet, 1962).

In this experiment, the staircase procedure treated failures and refusals as equivalent outcomes. Children received trials on increasingly steeper slopes until they fell or refused to walk, followed by trials on increasingly shallower slopes until they walked again successfully.

On the basis of pilot data, uphill trials began at 6° and downhill trials at 4° baselines. The experimenter increased slope 6° after each success until children fell or refused to walk, then repeated the trial for reliability. If they fell or refused twice in a row, she presented the shallow baseline slope to maintain their motivation to walk. Then, the experimenter presented a slope 4° shallower than the last failure or refusal. If children succeeded, slant increased by 6° and if they failed or refused twice in a row, the experimenter presented the baseline slope again. As the experimenter narrowed in on the upper and lower limits of children’s ability, she presented slopes in smaller 2° increments. The series continued until children met a 67% criterion for establishing walking boundary. Walking boundary was the steepest slope where children walked successfully at least two out of three times and failed or refused to walk at least two out of three times at the next 2° increment. The 67% criterion minimized total number of trials while ensuring at least four to six trials around walking boundary. Last, the experimenter presented all infants with at least one trial at 36° to see how they coped with the steepest hill. If at any time the experimenter was unsure how to score a trial, she repeated it. Up and down trials were blocked. Half of the infants went up hills first, and half went down first. Figure 2 shows typical protocols for uphill and downhill staircases for 2 children.

Figure 1. Walkway with adjustable slope. Top: Warm up on flat walkway. Parent stands at far end of walkway while experimenter follows alongside child. Bottom: Descending trial. Hydraulic pump lowers bottom platform causing walkway to slant at 20°.

Procedure

Children began each session on the flat walkway to become comfortable walking on the raised surface. First, children walked along the flat walkway to obtain measures of walking skill on flat ground. Then, children went up and down hills to determine their walking boundaries on slopes, perceptual judgments, and exploratory behavior. An assistant videotaped all trials on the flat walkway and slopes with the camera perpendicular to the length of the walkway. Last, children reclined on a changing table for measurements of body proportions. Typical test sessions lasted between 90 and 120 min.

Walking boundaries on slopes. The children began each trial raised and lowered the platform from 75.3 to 21.81 cm, causing the middle section of the walkway to be flat or to slope in 2° increments from 0° to 36°. Wooden poles at the corners of each platform provided the children with manual support, and a soft carpet provided traction and a cushion against falls. Safety nets extended along the sides of the walkway. An additional platform (83.6 cm wide × 76.75 cm long × 75.3 cm high) extended the horizontal length of the walkway from 244.5 to 321.25 cm for measuring walking skill on a flat surface. The carpet was removed, and butcher paper was rolled over the walkway for collecting footprint sequences.

1 Because a slope is analogous to the hypotenuse of a right triangle, change in slant covaries either with change in the length of the vertical leg or change in length of the horizontal leg and hypotenuse. Because of limited floor space and children’s limited endurance, I kept the length of the slope constant and allowed slant to covary with the height of the hill (steeper slopes had a larger vertical dropoff between starting and landing platforms). Although children could use information about both the slant and the height of slopes in the present experiment, results of a control experiment (Weiner & Adolph, 1993) showed that 14-month-old toddlers walk down shallow slopes but not down steep ones, even when the height of the hills is constant. The dimensions of the steepest slopes used in both studies were similar. In the control experiment, the 36° slope was 55 cm high and 94 cm long. In the present study, the 36° slope was 53.49 cm high from starting to landing platform and 91 cm long.
Because of the personalized nature of the staircase procedure, children received trials at different increments of slope, and some children had more trials than others. However, all children had trials on baseline slopes and at 36°, and all had trials at their walking boundaries and on slopes slightly shallower and steeper than boundaries. In total, children had between 10 and 25 uphill trials \((M = 16.94, SD = 3.74)\) and between 10 and 35 downhill trials \((M = 19.45, SD = 6.61)\). They had an average of 3.97 trials at baseline for up \((SD = 1.40)\) and 1.42 trials going up 36° \((SD = 0.76)\). They had an average of 5.84 trials at baseline for down \((SD = 3.22)\) and 1.82 trials going down 36° \((SD = 0.83)\).

It is important to note that estimates of walking boundaries may be conservatively biased. If children systematically refused to walk or deliberately fell on slopes where they really could walk, then trials would be scored as refusal or failure and walking boundaries would be underestimated accordingly. However, the practice of presenting baseline slopes after failures and refusals helped to renew children’s motivation to walk.

**Walking skill on flat ground.** As in previous research (Adolph et al., 1995a), I used footprint sequences to measure walking skill on flat ground based on the distances between foot placements. Children wore inked moleskin tabs on the bottom of their shoes at toes and heels, then walked over the flat walkaway toward their parents, leaving behind a trail of footprints. If children stopped walking or fell partway through a sequence, the trial was repeated. Thirty children contributed two footprint sequences and one child contributed only one usable sequence for testing the reliability of gait measures across consecutive trials.

**Body proportions.** After trials on slopes, the experimenter measured children’s body proportions using calipers and tape measure: head/chest circumference at eyebrows and nipple line (Ounsted & Moor, 1986); shoulder width/hip width across acromion processes and anterior iliac spines (Malina, 1984); recumbent height/leg length from anterior iliac spine to medial malleolus (Malina, 1984); leg length/crown-rump length (Shirley, 1931); and Ponderal Index (weight/height^{4} × 100). Larger ratios of shoulder/hip, and legs/crown-rump, and smaller ratios of head/chest, height/legs and Ponderal Index are associated with more mature body proportions (Malina, 1984; Ounsted & Moor, 1986; Shirley, 1931).

### Data Coding

**Walking Boundaries on Slopes**

All slope data collected online were recorded from videotapes of the sessions. Only data coded from videotapes were used in further analyses. A primary coder viewed the sessions, rescored each trial as success, failure, or refusal, and recalculated the walking boundaries according to the 67% criterion described above. Walking boundaries calculated from videocoding were in exact agreement with 98% of the boundaries calculated online. A second coder scored video data from 7 subjects to determine interrater reliability. Percent agreement for success, failure, or refusal was 91% for ascent and 97% for descent, and walking boundaries were identical to those determined by the primary coder in all cases except for one uphill protocol (22° vs. 20°).

### Perceptual Judgments

The ratio of attempts to walk divided by total number of trials indexed perceptual judgments: \((S + F)/(S + F + R)\). Figure 3 illustrates the logic of this “go ratio.” On slopes steeper than boundary, a large ratio will occur if there are a lot of failures,

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**Figure 2.** Typical staircase protocols for going up and down. Each trial was coded as success, S (walked safely), failure, F (tried to walk but fell), or refusal, R (slid, climbed, or avoided). The experimenter presented steeper slopes after successful trials and shallower slopes after failures or refusals to estimate walking boundaries (indicated by arrow) with at least 2/3 successes at boundary (shaded region) and 2/3 failures or refusals at the next 2° increment. #39 and #27 represent Baby 39 and Baby 27, respectively.

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Occasionally, children spontaneously went up during the downhill staircase or down during the uphill staircase (e.g., Trial 17 in top panel of Figure 2). After reaching the landing platform, they spontaneously stood up, turned, and went over the slope in the other direction although their parents remained behind in their original location. Thirteen children had spontaneous out-of-order trials going up, and 9 children had out-of-order trials going down. The number of spontaneous trials ranged from 1 to 7 for both up \((M = 2.23, SD = 2.05)\) and down \((M = 2.00, SD = 2.00)\). These trials were scored as success, failure, or refusal and used in calculations of walking boundaries.
PSYCHOPHYSICAL ASSESSMENT

\[(S+F)/(S+F+R) = \text{Attempts to Walk/Total No. of Trials}\]

If walk won't fall \(\rightarrow\) Steepest hill \(\rightarrow\) If walk will fall without falling

Low ratio \(\rightarrow\) underestimate abilities

High ratio \(\rightarrow\) overestimate abilities

Degrees Relative to Walking Boundary

\[\text{Figure 3. Top: Logic of go ratio. High ratio on slopes steeper than walking boundary indicates overestimation of abilities. Low ratio on slopes shallower than the boundary indicates underestimation of abilities.} \ S = \text{success}; \ F = \text{failure}; \ R = \text{refusal. Go ratio equals } (S + F)/(S + F + R). \ \text{Bottom: Grouping slopes relative to walking boundary (denoted by 0°). The four groups around the boundary each span } 8^\circ \text{ (denoted by their midpoints } \pm 5^\circ \text{ and } \pm 13^\circ). \ \text{The two most remote groups include remaining trials on hills at least } 18^\circ \text{ shallower or steeper than the boundary (} \pm 18^\circ).\]

indicating that children overestimated their abilities and tried to walk when they were likely to fall. On slopes shallower than boundary, a small ratio will occur if there are a lot of refusals, meaning that children underestimated their abilities and sometimes refused to walk when in fact they could. (The inverse "no go ratio," \(R/(S + F + R)\), yields the same information.) By definition, go ratios must be .67 or higher at walking boundary but can vary freely from 1 to 0 on slopes steeper or shallower than boundary. Also by definition, success is rare on slopes steeper than boundary, so that go ratios depend largely on the proportion of failures to refusals. This proportion is statistically independent from estimates of walking boundary, which treat failures and refusals the same. Likewise, failures are rare on slopes shallower than boundary, so that go ratios depend largely on the proportion of successes to refusals. Although the go ratio is not a pure measure of perceptual accuracy because, like any judgment, it includes participants' response bias (willingness to err on the side of caution or the side of boldness may contribute to decisions), it reflects the consistency of children's judgments over the test session. If children perceive slopes relative to their own ability, ratios should increase as slopes get shallower than walking boundary and decrease as slopes get steeper than boundary.

In principle there is a go ratio for every slope. For example, in Figure 2, Baby 39 had a go ratio of 1.0 at walking boundary, 1.0 at 18°, .67 at 20°, and so on. Baby 27 had a go ratio of 1.0 at walking boundary, .67 at 22°, and 0 at 24°, 28°, and 36°. However, in practice children received only one to three trials on most slopes, and they received trials on different slopes around boundary. To compile more meaningful ratios and to facilitate comparisons between children, I grouped trials on successive increments together and calculated a go ratio for each group of slopes. As shown at the bottom of Figure 3, I formed seven groups of slopes described by their midpoints: 0, \(\pm 5^\circ\), \(\pm 13^\circ\), and \(\pm 18^\circ\). These groups respectively correspond to walking boundary, hills slightly shallower or steeper than the boundary, an intermediate range of hills, and hills considerably steeper or shallower than the boundary. The four groups surrounding walking boundary each spanned 8°, and the two most remote groups of hills captured remaining trials on hills at least 18° shallower or steeper than walking boundary. The size of the groups maximized number of children contributing data and average number of trials per child, while preserving detail in the measurements. Table 1 shows the number of children with data at each of the seven intervals and how many trials they received.

The effect of grouping data across slopes for individual children is to create a more continuous index of perceptual judgments and to smooth out chance irregularities, especially on hills close to walking boundary, where children received most trials. For exam-
Table 1

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<tr>
<td>+13</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>+18</td>
<td>19</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 1: Number of Children and Number of Trials per Child in Each Group of Slopes.

ple, returning to the data in Figure 2, Baby 39 had one refusal and five failures in the +5° group of slopes spanning 18° to 24°. The go ratio for +5° would be .83, and ratios would decrease from 1.0 at walking boundary to 0 at +18°. Baby 27 had one success, one failure, and five refusals in the range of slopes slightly steeper than boundary. The go ratio for +5° would be .29, and it drops to 0 at +13°, the steepest increment with trials.

Method of Locomotion

The primary coder scored the following methods of locomotion from videotapes: walking, crawling on all fours, sliding (headfirst, in a sitting position, or backward headfirst), and avoiding. For trials scored as refusals, these data reflect whether children shifted from walking to a less precarious method of travel or simply avoided going onto the hills.

On uphill trials, children often flung themselves forward onto hills. The coders adopted a criterion of two feet on the hill before hands touch for scoring ascending trials as walking. On descending trials, children occasionally took one or two tiny steps onto a hill while holding onto a pole and then stepped back onto the starting platform. Coders used a criterion of three forward steps on the hill for scoring descending trials as walking. Children were scored as avoiding if they did not start onto hills within 60 s. A second coder scored the method of locomotion from 7 infants. Percent interrater agreement was 91% for ascent and 99% for descent.

Exploratory Activity

The primary coder scored children’s exploratory activity on the starting platform from videotapes.

Latency. Time from the beginning of a trial until starting onto the hill indicated children’s hesitation. Time to get into position and approach the slope was subtracted so that latency reflected only hesitation rather than difficulty of switching from one position to another. If children avoided traversal or fussed, the coder scored latency as 60 s or as the amount of time until the experimenter stopped the trial, whichever occurred first. If children started onto slopes right away, the coder scored latency as 0.1 s. Correlation coefficients for interrater reliability for 7 children were .97 for ascent and .99 for descent.

Touching. Codes for haptic exploration reflect only active touch (J. J. Gibson, 1962) and included patting or rubbing hands or feet over the surface, touching while looking, and rocking hands or feet over the brink of the hill. The primary coder counted accumulated duration of active touch by viewing videotapes frame by frame. Correlation coefficients for interrater agreement for 9 children were .83 for ascent and .95 for descent.

Shifts in position. Coders counted children’s exploration of different methods of locomotion by noting the number of discrete shifts in position on the starting platform. Multiple shifts would suggest that children tested what different positions felt like before committing themselves to going—alternative means for achieving a goal. Coders counted the following positions only if children held them for at least .5 s: standing, squatting, kneeling, sitting, crawling, lying prone with stomach down, backing, or using a pole as a railing or banister. For example, standing-to-backing to standing-to-prone equals three shifts in position. Although there are fewer viable methods for going uphill, children often explored nonviable alternatives (e.g., squatting) and often tested the same position several times during a trial (e.g., alternating between backing and prone). Percent exact interrater agreement for each category for 7 children was 89% for ascent and 84% for descent; correlation coefficients for number of shifts were .84 for ascent and .93 for descent.

Walking Skill on Flat Ground

Footprint sequences yielded measures of children’s walking skill on a flat surface. Only the middle section of each sequence was analyzed, where children had hit their stride (Breniere, Bril, & Fontaine, 1989). Coders identified the XY coordinates of each heel and toe print using a transparent grid (.1 inch units). A computer program transformed the coordinates into the measures of foot placement illustrated in Figure 4. Step length is the distance...
between heel prints of alternate feet, and stride length is the
distance between heel prints of the same foot; better walkers have
longer steps and strides (e.g., Burnett & Johnson, 1971; Clark,
Whitall, & Phillips, 1988). Step width is the lateral distance
between steps; it decreases as skill improves (e.g., Bril & Bremiere,
1992; McGraw, 1945). Foot rotation is measured by the angle of
toe-in or toe-out from heel prints; better walkers point their feet
more straight ahead (e.g., Shirley, 1931).

Dynamic base (the angle between the stride of one foot and the
step on the other foot) is not a traditional measure of walking skill.
It is a new measure designed to provide information about step
width, step length, and the relationship between them. I reasoned
that angles would approach 180° as children's walking skill im-
proved. (Adults walk so that their heels mark a nearly straight line
along the path of progression because step length is large and step
width is very small.)

Computer software calculated mean values for each sequence,
and computed the reliability of each measure across children's
footprint sequences. Correlation coefficients were reliable for ev-
every measure: step length (.71), stride length (.75), step width (.84),
foot rotation (.90), and dynamic base (.78). These values are
comparable to those obtained from footprint sequences of adults
(e.g., Boening, 1977). Data were pooled across sequences for
further analyses.

Results

Walking Boundaries on Slopes

Walking boundaries were a conservative estimate of the
steepest slope children could walk over without falling. Figure 5 shows a large range in walking boundaries for
uphill (8° to 24°) and downhill (6° to 28°). The distribution
of boundaries for ascent was negatively skewed; most chil-
dren (n = 19) had boundaries greater than 16°. The descent
distribution was positively skewed; fewer children (only 8)
demonstrated ability to walk down these steeper hills. On
average, children walked up steeper hills (M = 17.81°,
SD = 3.77°) than they walked down (M = 15.29°, SD =
5.76°); paired t(30) = 3.7, p < .001. Children's walking
boundaries for up were positively correlated with bound-
daries for down (r = .71), meaning that children had rela-
tively similar abilities walking in both directions. The high
positive correlation also lends support for the validity of the
staircase method.

Perceptual Judgments

Go ratios (S + F)/(S + F + R) indexed the accuracy of
children's perceptual judgments on slopes shallower and
steeper than their walking boundaries. Figure 6 shows av-
"average go ratios for up and downhill. Children nearly always
tried to walk on slopes shallower than boundary, rarely
balking when there was a high probability of success. In con-
trast, go ratios decreased sharply at each increment
steeper than boundary, meaning that attempts to walk de-
creased with the likelihood of falling. Average ratios de-
creased threefold from walking boundary to +18° for both
up (from .99 to .23) and down (from .94 to .11). The ratio
was nearly twice as high at each increment steeper than
walking boundary for up than down. Statistical comparisons
between up and down at matched slopes revealed differ-
ences only at +5° (Table 2). Note that sample sizes were
smaller for paired comparisons because some children did
not receive trials going both up and down +13° and +18°
(Table 1).

Figure 6 also points up the consistency of children's
judgments. The smooth decrease from walking boundary to
+18° indicates few reversals in go ratios. Most children
were remarkably consistent over trials. If they refused to
walk at a given hill, they also refused to walk on steeper
ones.

Method of Locomotion

When children refused to walk, they usually found an
alternative method of locomotion. Of 60 trials scored as
refusals for ascent, there were no trials where children
avoided going; instead they switched from walking to
climbing up on all fours. Of 184 trials scored as refusals for
descent, in 18% children avoided and in the other 82% they
Perceptual Judgments

<table>
<thead>
<tr>
<th>Go Ratios</th>
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<tbody>
<tr>
<td>Up</td>
</tr>
<tr>
<td><img src="image1" alt="Graph" /></td>
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Exploratory Activity

<table>
<thead>
<tr>
<th>Latency</th>
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<tr>
<td>Time (s)</td>
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<table>
<thead>
<tr>
<th>Touching</th>
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</thead>
<tbody>
<tr>
<td>Time (s)</td>
</tr>
<tr>
<td><img src="image3" alt="Graph" /></td>
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</table>

<table>
<thead>
<tr>
<th>Shifts</th>
</tr>
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<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td><img src="image4" alt="Graph" /></td>
</tr>
</tbody>
</table>

Figure 6. Mean values of go ratios and three measures of exploratory activity. S = success; F = failure; R = refusal. Go ratio equals \((S + F)/(S + F + R)\).

used an alternative method of travel (9% crawled, 3% slid headfirst on their bellies, 39% slid sitting, and 32% scooted down backward feet-first). Although each method was physically possible for all children, they tended to stick with preferred ways of going—mostly sitting and backing feet-first.

Exploratory Activity

Children rarely explored before going up, regardless of slope. In contrast, children hesitated, touched, and tested different positions before starting down risky slopes. As shown in Figure 6, downhill exploration increased as go ratios decreased, although in principle refusals did not require exploration (children could immediately slide down). Table 2 shows results of statistical comparisons between up and down at walking boundary, \(+5^\circ\), and \(+18^\circ\).

Latency. Latency to start up hills ranged from 0.1 to 51.7 s, but on most trials children did not hesitate to go, even on impossibly steep hills (\(Mdn = 0.1\) s). Of 513 uphill trials, only 10% involved latency greater than 1.0 s. There was no difference in outcome between trials in which children hesitated and trials in which they charged ahead. Of 415 trials where latency was 0.1 s (median), 54% were successes, 35% were failures, and 10% were refusals. Of 98 trials where latency was greater than 0.1 s, 51% were successes, 28% were failures, and 21% were refusals.

Latency to start down ranged from 0.1 to 60 s. Although children did not hesitate on most downhill trials (\(Mdn = 0.2\) s), of 592 trials coded, 42% had latency greater than 1.0 s. In contrast to uphill, latency was related systematically to children's walking boundaries. Children hesitated at walking boundary and slopes steeper than boundary. In addition, latency was related to trial outcome. If children hesitated, even for a brief moment, they were more likely to refuse to walk than if they plunged straight down. Of 307 trials where latency was less than or equal to 0.2 s (\(Mdn\)), 70% were successes, 21% were failures, and 9% were refusals. Of 286 trials where children hesitated more than 0.2 s, 35% were successes, 14% failures, and 53% refusals. During the time they hesitated, children looked, touched, tested positions, asked for help, or evaded the problem by pulling on the nets or picking lint off the carpet.

Touching. Children rarely touched slopes before starting up, regardless of slant. Of 523 trials coded for ascent, there were only 27 touch trials (5%) spread over 12 children, and touches were extremely brief; accumulated duration of these touches ranged from 0.5 to 6.2 s, \(M = 2.4\) s. On 26 of the touch trials, children poked out a foot to probe the hill, and on one trial a child touched with both feet and hands.

In contrast, most children (\(n = 27\)) touched hills before going down, but touches were limited to walking boundary and steeper slopes. Of 602 downhill trials, children touched

<table>
<thead>
<tr>
<th>Table 2</th>
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<tbody>
<tr>
<td>Results of paired t tests</td>
</tr>
<tr>
<td>Measure</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Go ratio</td>
</tr>
<tr>
<td>Latency</td>
</tr>
<tr>
<td>Touching</td>
</tr>
<tr>
<td>Shifts</td>
</tr>
</tbody>
</table>

Note. The \(n\) values refer to the number of children receiving trials going both up and down. Dashes indicate \(t\) tests were not performed because only 3 children contributed data to both up and down at \(+13°\).

\(* p < .05\) \quad ** p < .01\) \quad *** p < .001.
on 137 (23%). These touches were generally brief, ranging from 0.5 to 34.3 s (M = 4.3 s). Refusals were more likely on touch trials than no-touch trials, but children often walked after touching (39% trials). Of 137 touch trials, 25% were successes, 14% failures, and 61% refusals. Of 460 no-touch trials, 60% were successes, 18% failures, and 21% refusals. On 106 touch trials, children probed gingerly with one foot or rocked back and forth with both feet at the brink. On 17 trials, children patted or rubbed with their hands. On the remaining 14 trials, children touched with hands and feet.

*Shifts.* Children rarely explored different methods of travel before starting uphill. Discrete shifts in position ranged from 0 to 4, but only 2% of 520 uphill trials had more than 1 shift. When children switched from walking, they shifted one time and started right up on all fours. Figure 6 illustrates this point clearly because mean values never exceed one shift.

For descent, children tested alternative positions at walking boundary and steeper increments. Mean values exceed one shift at each increment steeper than walking boundary and ranged from 0 to 10. Twenty-six children explored multiple positions on at least one trial, 4 shifted only once, and 1 child never at all. On 16% of 601 downhill trials, children tested multiple positions before going. On an additional 16%, children shifted only once and usually slid right down. Exploratory shifts were nearly always followed by refusals to walk, suggesting that children had already decided that hills were too steep to walk safely. Of 96 multiple shift trials, 93% were refusals, 6% were successes, and 1% were failures.

Two points about exploratory shifts are especially interesting. First, of the 96 multiple shift trials, on 45% of them 15 children tried a position or two and then stood back up before trying other positions, as if returning to a normal baseline before venturing out again. There is no physical necessity for returning to a stand, for example, in a sitting—standing—backing sequence of shifts, but there is a psychological reason if children consider each alternative relative to their normal method of travel. Second, on 48% of the multiple shift trials, 16 children used the poles for support as they moved from one position to another. They clung to the poles as an adult would use a railing in a tricky situation. On single shift trials, children were less likely to use the poles (22% of 95 trials spread over 9 participants).

*Sources of Individual Differences*

There were individual differences in the accuracy of children's perceptual judgments. Some infants were better perceivers than others—decrease in go ratios was geared more closely to their walking boundaries. In fact, the steady decrease in mean go ratios (Figure 6) was largely the result of individual differences in how children coped with slopes. Data from a subset of children produced the sharp drop in go ratios at +5°. I used individual differences in perceptual judgments as an outcome measure to examine whether exploratory activity, walking ability, locomotor experience, and body proportions were related to perception of affordances. Note that go ratios are statistically independent of each predictor. In principle, children could succeed, fail, or refuse in any proportion, regardless of how long they hesitated or touched, how steep their walking boundary was, and so on.

I grouped children according to the slope where their go ratios dropped to .50 or lower and decreased thereafter. This is the slope where children consistently refused to walk. As shown in Table 3, there are four possible go-ratio groups corresponding to the groups of slopes steeper than walking boundary: (A) refuse to walk on slopes slightly steeper than boundary, denoted by +5°, (B) refuse on intermediate slopes, +13°, (C) refuse impossibly steeper slopes, +18°, and (D) never refuse to walk. Go ratios are most closely geared to walking boundaries for Group A, least for Group C, and unrelated to boundaries for Group D. The grouping reflects only consistent ways of responding to ascent and descent and is not meant to reflect underlying differences in temperament across tasks. In fact, most children did not treat ascent and descent in the same way. Only 2 children were in Group A for both up and downhill, 1 was in Group B for both, 3 in Group C for both, and 2 in Group D for both.

*Individual Differences in Ascent*

Go-ratio groups for uphill were related to walking ability and experience but not to exploratory behavior. Figure 7 and the top panel of Table 3 show the four patterns of perceptual judgments and number of children in each go-ratio group for ascent. Girls and boys were spread evenly across groups; \( \chi^2(3, N = 31) = 5.30, p > .10 \). All children fell at some point trying to walk up, and most children walked indiscriminately (Group D) or tried walking until +18° (Group C). Note that children in Group C did not receive trials at +13°, represented by breaks in the x axis. This is an artifact of the staircase procedure, which normally does not require trials on slopes steeper than +5° to identify walking boundary (see Figure 2). In most cases, children only had trials in the +13° and +18° intervals because the additional trials at 36° were steeper than the +5° interval. It is therefore possible that infants in Group C might have refused to walk sooner had they received trials in the +13° range.

*Exploratory activity.* Overall, there was virtually no hesitation, touching, or testing of means—ends relations before starting up hills, and no differences emerged from examination of individual children. Hesitation before starting up was limited to a few trials by a few children in Groups A and B on slopes steeper than walking boundary. Children in all groups rarely touched slopes before going up, regardless of increment. The 12 touchers and 19 nontouchers were distributed equally across groups, \( \chi^2(3, N = 31) = 3.12, p > .10 \). The few exploratory shifts in position were limited to a few children in Groups A and B.

*Walking boundaries on slopes.* Children in Groups A and B and had slightly higher walking boundaries than did children in Groups C and D (Table 3). An analysis of variance (ANOVA) revealed differences between groups,
Table 3
Individual Differences in Up and Down: Mean Values and Standard Deviations of Walking Boundaries on Slopes, Walking Skill on Flat Ground, and Walking Experience for Go-Ratio Groups

<table>
<thead>
<tr>
<th>Measure</th>
<th>Go-ratio groupa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A, +5°</td>
</tr>
<tr>
<td></td>
<td>M    SD</td>
</tr>
<tr>
<td>Uphill</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>4</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>3</td>
</tr>
<tr>
<td>Female</td>
<td>1</td>
</tr>
<tr>
<td>Walking boundaries</td>
<td></td>
</tr>
<tr>
<td>(degrees)</td>
<td>21.50</td>
</tr>
<tr>
<td>Flat ground</td>
<td></td>
</tr>
<tr>
<td>Base (degrees)</td>
<td>161.74</td>
</tr>
<tr>
<td>Width (cm)</td>
<td>8.80</td>
</tr>
<tr>
<td>Experience (days)</td>
<td>94.50</td>
</tr>
<tr>
<td>Downhill</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>17</td>
</tr>
<tr>
<td>Sex</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>9</td>
</tr>
<tr>
<td>Female</td>
<td>8</td>
</tr>
<tr>
<td>Walking boundaries</td>
<td></td>
</tr>
<tr>
<td>(degrees)</td>
<td>15.41</td>
</tr>
<tr>
<td>Flat ground</td>
<td></td>
</tr>
<tr>
<td>Base (degrees)</td>
<td>155.24</td>
</tr>
<tr>
<td>Width (cm)</td>
<td>11.43</td>
</tr>
<tr>
<td>Experience (days)</td>
<td>88.71</td>
</tr>
</tbody>
</table>

a Slope of go ratio was less than .50.

F(3, 27) = 9.28, p < .001. Student-Newman-Keuls comparisons showed differences only between Group C and the other groups.

Walking skill on flat ground. Children displayed a wide range in walking skill on flat ground. Mean step lengths ranged from 16.74 to 31.35 cm, strides from 30.66 to 61.37 cm, step widths from 6.13 to 18.20 cm, dynamic base angles from 133.27° to 169.50°, and foot rotation from −12.12° to +28.12°. There were significant correlations between gait variables reflecting expected improvements with better walking skill (Table 4). Children with longer steps and strides walked with their feet closer together. Surprisingly, foot rotations were not related to any other measures. Although dynamic base is a new measure of walking skill, it was correlated with the traditional measures in a reasonable manner and yields information about both the width and length of children's steps (positive correlations with step and stride lengths and negative correlations with step width).

Several measures of walking skill on flat ground were

Perceptual Judgments

![Figure 7](image_url)

Figure 7. Ascent: Individual differences in accuracy of perceptual judgments based on the slope where go ratios decreased below .50. S = success; F = failure; R = refusal. Go ratio equals (S + F)/(S + F + R).
significantly correlated with walking boundaries on slopes (Table 4), suggesting that estimates derived from the staircase method were valid. Dynamic base was the strongest correlate of walking boundaries for uphill. Walking skill on flat ground was also related to individual differences in perceptual judgments for uphill. As summarized in Table 3, children in Groups A and B tended to have larger dynamic base angles, $F(3, 27) = 3.76$, $p < .022$, and smaller step widths, $F(3, 27) = 3.65$, $p < .025$, than children in Groups C and D; in both cases, Student-Newman-Keuls procedure revealed differences only between Groups B and C.

**Locomotor experience.** Parents provided information about their children’s locomotor experience. Walking experience ranged from 10 to 137 days ($M = 76.87$, $SD = 34.42$) at the time of testing. Sixteen children had first belly crawled, then crawled on hands and knees before starting to walk. Thirteen children had crawled only on hands and knees before walking. Two children had never crawled. (They had 14 and 112 days of walking experience, respectively.)

Length of walking experience was positively correlated with walking boundaries for ascent ($r = .62$). Stepwise multiple-regression analyses using all gait measures and walking experience allowed only dynamic base and walking experience to enter the equation for uphill ($R = .81$). Because walking experience was also correlated with dynamic base (Table 4), I used partial correlations to examine independent effects of each variable on walking boundaries. With walking experience partialed out, dynamic base was still a significant correlate of walking boundaries for ascent (partial $r = .67$).

Walking experience was also related to children’s perceptual judgments going up slopes. As summarized in Table 3, children in Groups A and B had more walking experience than did children in Groups C and D. An ANOVA revealed differences between groups, $F(3, 27) = 4.15$, $p < .02$. Variability was high, and Student-Newman-Keuls comparisons revealed differences only between Groups B and C.

**Body proportions.** Children’s body proportions showed a narrow range of values: Ponderal index (1.78–2.44), height/legs (2.18–2.50), legs/crown rump (0.62–0.74), head/cheek (0.87–1.06), and shoulder/hips (1.31–1.71). Coefficients of variation were less than 8% for all ratios except shoulder/hip. Only the ratio of height/leg was correlated with walking boundaries for uphill ($r = -.41$, $p < .022$), suggesting that children with more mature proportions could walk up steeper hills. There were no significant correlations between body proportions and length of walking experience or footprint measures. Body proportions were not related to go ratio groups for ascent.

To summarize results for uphill, individual differences in go ratios were related to walking boundaries on slopes, walking skill on flat ground, and length of walking experience (Table 3). Skilled, experienced walkers tended to be more accurate when going uphill. There was no relationship between perceptual judgments and exploratory activity or body proportions.

**Individual Differences in Descent**

In contrast to ascent, individual differences in perceptual judgments for going downhill were not related to walking skill or experience but were strongly related to exploratory activity. As above, I grouped children according to the slope at which go ratios decreased to .50. The bottom panel of Table 3 and top panel of Figure 8 show individual differences in children’s go ratios for downhill and the number of children in each go ratio group. Boys and girls were spread evenly across groups, $X^2(3, N = 31) = 0.87$, $p > .10$. Most children were more wary about going downhill than uphill; more than half of the sample balked on downward slopes slightly steeper than boundary (Group A). Seven children in Group A never tried to walk down slopes steeper than boundary; their go ratios dropped to 0 at the first $+2^\circ$ increment. Five children in Group A even underestimated their walking boundaries and sometimes refused to walk down $-5^\circ$ (ratios ranged from .22 to .89), although by definition all walked at least two thirds of the time at boundary.

**Exploratory activity.** Exploration closely mirrored perceptual judgments for descent. As shown in Figure 8 (reading down columns), children hesitated, touched, and shifted positions at approximately the same slopes where their go ratios decreased. That is, behaviors on the starting platform predicted children’s success at navigating the hills safely.

Latency and go ratios run in mirror images across rows one and two of Figure 8. Fewer children in Group A fell if
they started down hills without hesitating, \( \chi^2(3, N = 31) = 8.45, p < .05 \), but there were no differences between groups if they hesitated for at least 0.2 s before starting down. If children stopped momentarily before going over the brink, they were equally likely to respond appropriately.

Touching mirrored go ratios for Groups A, B, and C (compare rows 1 and 3 in Figure 8). Children in Group A began touching at walking boundaries, Group B touched slightly steeper hills, and Group C steeper still. Two children in Group D touched indiscriminately (sometimes shallower and sometimes steeper than boundaries) and nonetheless plunged over and fell. Overall, Groups A and B were more likely to touch than were Groups C and D, \( \chi^2(3, N = 31) = 8.69, p < .05 \). Only 4 children never touched—2 each in Groups C and D. Proportionately fewer children in Group A than in other groups fell after touching (3 of 17), \( \chi^2(3, N = 31) = 13.59, p < .005 \), but there were no differences between groups on trials with no touching, \( \chi^2(3, N = 31) = 4.92, p > .10 \).

Most children tested multiple shifts in position before
starting down slopes, and again exploration mirrored perceptual judgments for each group (Figure 8, rows 1 and 4). Groups A, B, and C tested alternative positions at approximately the same slopes where go ratios decreased. Children in Group D never explored alternative means of descent.

**Walking boundaries.** In contrast to ascent, for descent, walking boundaries were not related to individual differences in go ratios (Table 3). Variability was high, and an ANOVA showed no differences between groups: \( F(3, 27) = 0.33 \).

**Walking skill on a flat surface.** For descent, several measures of walking skill on flat ground predicted walking boundaries on slopes, but correlations were not as high as for ascent (Table 4). Dynamic base was the single best predictor of walking boundaries for going up and down, although step width was nearly as good for descent. Unlike ascent, there was no relationship between any measures of walking skill on a flat surface and go ratio groups for descent. Table 3 shows mean values of base and width for each group.

**Locomotor experience.** Length of walking experience was correlated with walking boundaries for descent, but not as strongly as dynamic base (Table 4). A stepwise multiple-regression analysis using all gait measures and walking experience allowed only dynamic base to enter the equation for downhill (\( R = .54 \)). Dynamic base remained a significant correlate of walking boundaries, even with walking experience partialled out (\( r = .43 \)). In contrast to ascent, walking experience was not related to individual differences in perceptual judgments, \( F(3, 27) = 1.96, p > .10 \). Table 3 shows mean values for each group.

In addition, specific experiences with descent were not related to go ratios. Ten parents reported their children had gone down a toddler slide independently. Seventeen children had gone down a short flight of stairs independently; 14 scooted backward feet-first, and 3 went down sitting. Twenty-nine had descended from furniture by scooting backward feet-first, indicating that nearly every child could use this method of locomotion in an appropriate context. Four children had experienced serious falls after walking onset. Three fell down stairs (1 boy in a mechanical baby walker, 1 girl broke her leg, and 1 girl’s parents provided no further details). The other child split his lip when he fell while walking and stopped walking for several days.

Experience going down stairs and playground slides did not affect perceptual judgments on slopes. Of the 14 children who backed feet-first down stairs, 10 used this strategy at least one time for descending slopes (test between proportions, \( z = 2.22, p < .013 \)). However, knowing a strategy for getting down did not mean that children knew how to use the strategy. Children with stair and slide experience were evenly distributed across the four groups: stairs, \( \chi^2(3, N = 31) = 3.30, p > .10 \); playground slides, \( \chi^2(3, N = 31) = 3.67, p > .10 \). Similarly, having experienced a serious fall before the lab visit did not predict children’s wariness descending slopes. Of the 4 children reported to have experienced serious falls, 2 were in Group A for descent, 1 in Group B, and 1 in Group D for descent, \( \chi^2(3; N = 31) = 3.28, p > .10 \).

**Body proportions.** Body proportions were not related to walking boundaries for descent, and there were no differences between go-ratio groups.

In sum, individual differences in perceptual judgments were predicted by children’s exploratory activity but not by their walking ability, locomotor experience, or the shapes of their bodies.

**Control for Trial Order Effects**

To control for trial order effects, children received trials on shallow baseline slopes interspersed with staircase trials (4° and 6° slopes in Figure 2). I examined whether children became tired or bored over the lengthy sessions by analyzing whether there were changes in latency or touching on baseline trials. There was no correlation between trial number and latency (\( r = .06 \)) or touching (\( r = -.11 \)) for ascent at 6° baselines, and no correlation between trial and latency (\( r = .04 \)) and touching (\( r = .01 \)) for descent at 4° baseline slopes. Children appeared to enjoy the sessions and were enthusiastic about going up and down slopes.

**Discussion**

This research examined the origins of prospective control by observing how novice walkers monitor a sloping path ahead. I devised a psychophysical procedure to estimate children’s walking boundaries on slopes and at the same time assessed the accuracy of their perceptual judgments with a go ratio on hills steeper and shallower than walking boundaries. Together, these two measures tell us the extent of children’s ability to perceive affordances for walking up and down hills. This is the first study to quantify the accuracy of perception of affordances in nonverbal subjects.

On the whole, most 14-month-old toddlers were good perceivers of affordances for locomotion over slopes. They were good perceivers in two respects. First, children gauged hills relative to their own abilities and the different task demands of going up versus down. Second, they knew how to discover what their own abilities were by exploring in appropriate ways at opportune times. I discuss each point below, but first I turn to the staircase method for estimating walking boundaries.

**Walking Boundaries on Slopes**

The modified staircase procedure is a new method for estimating infants’ physical abilities relative to change in environmental properties—in this case, walking on slopes. As in earlier studies, children could walk up steeper hills than down, emphasizing that walking downhill is a more difficult biomechanical task (e.g., Adolph et al., 1993; Giacalone & Rarick, 1985). More skillful and experienced walkers on flat ground were also better walkers on slopes. Although the design of the staircase procedure was biased conservatively toward shallower boundaries, correlations with kinematic measures of walking skill on flat ground and
length of walking experience suggest that estimates of walking boundaries on slopes were valid.

A new measure of walking skill on flat ground—dynamic base—was the single best predictor of walking boundaries going up and down slopes, explaining more variance independently than did measures of walking experience or body proportions. Intercorrelations between footfall measures show that dynamic base yields information about both the frontal and sideways displacement of children’s steps; base is positively correlated with step and stride lengths, and negatively correlated with step width. In other words, children who walk on flat ground with their feet along a straighter path do better at walking up and down slopes. They may have better postural control and sway less from side to side.

Length of walking experience was only weakly correlated with measures of walking skill on flat ground and walking boundaries on slopes. The low correlations may be due to error in parents’ reports (Walk, 1966). However, experience measures are problematic for conceptual reasons as well. Length of walking experience is simply the number of days between the first day of walking and the test session. It is not a direct reflection of how much practice children get, as wearing a pedometer would be, or of the variety or frequency of children’s exposure to different surfaces. Furthermore, in early days of walking, experience and skill are only moderately correlated (e.g., Brill & Brienere, 1992). Some children are better walkers from the start, and some improve more quickly than others. In contrast, footprint sequences are objective, reliable measures obtained firsthand in the laboratory, and they directly reflect children’s walking skill.

Body proportions were poor predictors of walking boundaries. There was little range in measures—most children were built like cylinders or inverted triangles. There were no significant correlations between measures of proportions, and no evidence that children with more mature proportions walked sooner or better than children with more babychish proportions. Of five measures, only the ratio of leg length to height was related to walking boundaries on slopes, and only for ascent. In contrast to studies with adults (e.g., Warren, 1984; Warren & Whang, 1987), for novice walkers the limited range in body dimensions appears to be less important than the large range in postural control, reflected more directly by footprint measures.

**Perceiving Affordances**

Most children perceived different possibilities for locomotion in relation to their walking boundaries on slopes and the different task constraints of going up versus down. On average, children slightly overestimated their own abilities. Go ratios were high on slopes shallower than boundary but decreased steadily on slopes steeper than boundary. This means that attempts to walk decreased with the likelihood of walking safely, a likelihood that depended on each child’s ability. In accordance with earlier findings (Adolph et al., 1993a), children were more wary of going downhill than going up, approaching declines with more concerted caution and inclines with a more lackadaisical, playful attitude. In fact, most children treated going up and down as different tasks, as shown by the measures that correlate with perceptual judgments and by the very different exploratory activity accompanying the two.

**Uphill.** Individual differences in perceptual judgments for ascent were related to walking ability and experience. Better perceivers (Go-Ratio Groups A and B) were better walkers on flat ground (narrower base of support) and slopes (steeper walking boundaries) and had more days of walking experience. There were no differences in children’s body proportions or exploratory activity.

Children did not hesitate, touch slopes, or explore different ways of going before starting uphill. They just charged up hills regardless of how steep they were—a striking example of learning by doing. Children were not frustrated or upset by falling during ascent, and safely caught themselves after mishaps. Many children persisted in attempts to reach the summit after falling uphill, even when efforts resulted in sliding back down several times. Usually persistence paid off. Of 176 ascending trials where children tried to walk but fell, 72% of them eventually resulted in success as children climbed the hill on all fours. Learning by doing is a sensible strategy for the task of going uphill, and all four groups of children used it.

For ascent, what appears to separate better perceivers from poor ones is their ability to benefit from brief glances at the hill. Go-Ratio Groups A and B better knew when to walk and when to crawl, without needing to hesitate or touch slopes. Similarly, adults in Kinsella-Shaw et al.’s (1992) study could detect whether slopes were too steep to walk up without needing to touch them with their feet. Just looking appeared to yield enough information to detect affordances. It is possible that individual differences stem from different levels of visual attention. Better walkers may be better perceivers for going uphill because they attend to subtle visual cues that are not noticed by the other children, ignore information that distracts them, or both. For example, Group A and B may better differentiate optical information for postural stability (Schmuckler & Gibson, 1989; Stoffregen, Schmuckler, & Gibson, 1987), resulting in better postural control on flat ground and slopes. Better postural control would be reflected by smaller step widths, larger dynamic base angles, and steeper boundaries on slopes. Predicting one’s own postural stability ahead of time might result in fewer failures going up slopes.

**Downhill.** Most children were more wary of falling downhill than uphill, regardless of their walking skill or previous experiences. Individual differences in perceptual judgments for descent were not related to walking boundaries on slopes, walking skill on flat ground, or length of walking experience. In addition, knowledge of how to get down stairs or playground slides did not help children to know when hills were too steep to walk down in the laboratory context, and a serious fall at home did not cause children to behave more cautiously going down slopes. Similarly, McGraw’s (1935) trained twin backed feet-first down slopes for months before he used this strategy to get down from high stools, despite daily practice with both
tasks. Results from a recent longitudinal study also suggest that, at first, learning about affordances may be specific to each environmental context and task (Adolph, 1993). Infants learned to detect affordances for crawling down hills, but there was no transfer from crawling to walking.

For descent, what separated good perceivers (Go Ratio Groups A and B) from poor ones (Groups C and D) was their exploratory activity. Most children hesitated, touched slopes, and tested alternative ways of going before starting down hills. This difference in exploratory behavior between up and downhill replicates and extends earlier findings (Adolph et al., 1993a). Most important, each type of exploratory activity closely mirrored perceptual judgments. Good perceivers knew what type of exploratory activity to use and when to use it. On safe slopes shallower than boundary, they glanced briefly and walked right down. They used more judicious cautious probes and tested alternative means of descent at walking boundary and on slightly steeper slopes. Good perceivers also appeared to benefit more from exploration. Proportionately fewer children in Group A failed on trials where they explored by touching. Poor perceivers in Group C used each type of exploratory activity, but not at the most opportune times. They used a glance-and-plunge strategy until faced with impossibly steep slopes, where hesitation, touching, and shifts in position increased sharply. Children in Group D never hesitated or shifted positions before starting down. Like the crawlers in Adolph et al.’s (1993a) study, they touched slopes indiscriminately, plunged down nonetheless, and fell.

Function of Exploratory Activity

Children must detect information for affordances through the use of exploratory activity. Prospective control requires use of one kind of movement to obtain information about another kind of movement. Good perceivers appeared to cope with slopes by coordinating exploratory procedures into a three-step process; each step served a different function and was sensitive to the different task demands of going up versus down. (a) Children took a quick glance at the slope. If it looked safe, they plunged ahead. The glance-and-plunge strategy is an example of learning by doing. There was little risk from falling when walking uphill, regardless of slope, and little risk when walking downhill on slopes shallower than boundary. Learning by doing functions to yield the maximum amount of information in the shortest amount of time. (b) If a quick glance from the starting platform hinted at something amiss, then children hesitated, looked carefully, and touched. These cautious probes served to turn up information about whether slopes were safe for walking. Children refused to walk on slightly over half of such trials and walked on the others. Usually decisions were accurate because few touch or hesitation trials resulted in failure. (c) If a touch suggested danger from falling, then children generated alternatives and tried them out before going. Children appeared to use means-ends exploration after they had decided not to walk in order to figure out a safer means of descent. They noticed the poles on multiple shift trials and used them as a railing, like a tool or partial means toward achieving a goal, but ignored the poles on trials where they did not shift positions. Children often stood up between shifts, as if using their normal vantage point as a base from which to consider alternatives. Usually multiple-shift trials ended when children slid safely down.

This three-step process is not a rigid program. Children’s behavior was much more flexible than that. However, the results are consistent with these types of exploration, each of them serving a different function and occurring in a loose temporal order. The data suggest that the sort of knowledge that separates good perceivers from poor ones is not a static concept of their own abilities or a fixed routine for coping with slopes. What good perceivers do is gauge their abilities on-line, from moment to moment and task to task. They know how to explore, when to explore, and what information to take from it.

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