Crawling versus Walking Infants’ Perception of Affordances for Locomotion over Sloping Surfaces

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Adolph, Karen E.; Eppler, Marion A.; and Gibson, Eleanor J. Crawling versus Walking Infants’ Perception of Affordances for Locomotion over Sloping Surfaces. Child Development, 1993, 64, 1158–1174. 14-month-old toddlers vs. 8.5-month-old crawling infants were encouraged to ascend and descend a sloping walkway (10°, 20°, 30°, and 40°). Infants in both locomotor groups overestimated their ability to ascend slopes. However, on descending trials where falling was more aversive, most toddlers switched from walking to sliding positions for safe descent, but crawlers plunged down headfirst and many fell at each increment. Toddlers touched and hesitated most before descending 10° and 20° slopes, and they explored alternative means for descent by testing out different sliding positions before leaving the starting platform. In contrast, crawlers touched and hesitated most before descending 30° and 40° slopes, and they never explored alternative sliding positions. In addition, we analyzed measures of locomotor skill and experience in relation to children’s ability to perceive affordances. Findings indicate that children must learn to perceive affordances for locomotion over slopes and that learning may begin by fine-tuning of exploratory activity.

The most dramatic motor achievement in the first year of life is the onset of independent locomotion, first crawling and later walking. These milestones reflect radical change in children’s bodily structure, coordination, and control. As infants’ locomotor capabilities change, new features of the environment are available for exploration and exploitation. However, variations in the terrain that are easily negotiated by older children challenge the developing skills of crawlers and toddlers, especially maintenance of balance. Thus, children must tailor locomotion both to their own developing capabilities and to properties of the terrain.

Previous research has focused on infants’ locomotion over an apparent drop-off or over surfaces varying in rigidity. For example, many visual cliff studies found that crawling infants refused to venture over the visually specified drop-off, despite haptic information for a safe surface of support provided by the Plexiglas covering the deep side (e.g., Bertenthal & Campos, 1984; E. J. Gibson & Walk, 1960; Richards & Rader, 1983; Walk, 1966). In several experiments, E. J. Gibson and colleagues found that toddlers differentiated a rigid plywood versus a squishy waterbed by their exploratory behavior and mode of locomotion (Gibson et al., 1987). Toddlers manually explored the waterbed and observed the consequent ripples, and they crawled rather than walked over it. However, both surfaces were safe to crawl over, and crawling infants crossed them with little prior exploration.

Few studies have examined children’s locomotion over sloping surfaces. In her...
classic co-twin study, McGraw (1935) observed that the trained twin mastered ascent of ramps before descent, but progress in both directions was rapid with daily practice. More recently, Giacalone and Barick (1985) found that preschoolers walked farther along narrow beams slanting upward than along horizontal beams or beams slanting downward. In a preliminary study with toddlers in a free play situation, children performed more visual and haptic exploration before sliding down 35° slopes than before ascent (Adolph, Eppler, & Gibson, in press; Adolph, Gibson, & Eppler, 1988). All children attempted more ascents than descents, often trying to climb up a slope but failing to reach the platform. Only one child tried to walk down a slope, and he fell headlong, requiring rescue by an experimenter. These studies indicate that ascent and descent present different biomechanical challenges to upright locomotion, and that young infants may perceive these differences.

We examined the development of guided locomotion over slopes within the theoretical framework provided by the concept of affordances (E. J. Gibson, 1982, 1988). In his ecological approach to perception, J. J. Gibson (1979) coined the term affordance to describe the reciprocal relation, or "fit," between physical properties of actor and environment that is required to perform a given action. According to Gibson, information specifying affordances is available in light or sound reflecting from surfaces of the environment and one’s own body, and through deformation and stretching of muscles, skin, antennae, whiskers, and so on (Lee, 1991). Gibson claimed that animals guide action adaptively by perceiving affordances, and that movement, in turn, generates new information for perceptual systems.

Although in several studies the various cues for infants’ perception of slant in a picture plane have been investigated (e.g., Degelman & Rosinski, 1971; Rosinski & Levine, 1976; Slater & Morrison, 1985), locomotion over slopes requires perception of geographical rather than optical slant—that is, the slant of a supporting surface relative to gravity and the body rather than relative to the retina (J. J. Gibson, 1962). In addition, frictional properties of the surface and the length, width, and height of the slope may interact with surface slant to affect affordances for locomotion. An experiment with adults suggests that geographical slant is specified visually and through haptic/pro-

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 prioceptive information by touching the slope with hands or feet. Kinsella-Shaw and Shaw (1959) showed that adults accurately detect affordances for walking up slopes. Subjects indicated whether a large visible incline was the same slant as a small hidden ramp on which their foot rested. Angles between seen and felt ramps were congruent, and judgments of walkable inclines corresponded closely to empirically derived thresholds for walking versus climbing up on all fours.

To test infants’ perception of affordances for locomotion over slopes, we encouraged toddlers and crawlers to ascend and descend a large sloping walkway. Some slopes were too steep to walk or crawl over safely. Based on visual cliff studies, we expected infants in both locomotor groups to avoid plunging headfirst down steep slopes with a large vertical drop-off. Of special interest was the role of two types of self-initiated exploration: touching the slope with hands or feet, and exploring alternative means for traversal (various sliding and climbing positions). The results of our preliminary study (Adolph et al., in press) suggested that infants would engage in more haptic/pro-prioceptive exploration before descent where falling has more serious consequences. McGraw’s (1935) trained twin learned new means to navigate slopes while attempting to crawl in the typical fashion, rather than by exploring various alternatives before leaving the starting platform. In particular, she noted that scooting backward feet first toward a goal is a “very distinct milestone in development” (p. 144). Based on our preliminary study, we expected this sort of “learning by doing” on ascending trials, where slips and falls are more easily controlled. However, we were more interested in whether infants would explore alternative means to descend slopes before starting down.

Experiment 1

In Experiment 1 we assessed toddlers’ perception of affordances for walking over slopes. We observed children’s spontaneous exploration to discover how they obtained information specifying affordances for locomotion. In addition, we examined whether locomotor skill and experience were related to perception of affordances. In previous research, the only predictor of infants’ behavior in a locomotor task has been the interrelated variables of age and experience (see Adolph et al., in press, for a review). How-
ever, measures of experience are often unreliable when dependent on parental reports (e.g., Walk, 1966) and are difficult to interpret. In contrast, gait sequences on a horizontal surface may be obtained firsthand in the laboratory. Longer step length, and decreased step width and rotation, are associated with improvements in walking skill, reflecting better postural control during periods of single limb support (e.g., Burnett & Johnson, 1971; McGraw, 1935; Scrunton, 1969; Shirley, 1931). We expected toddlers with more walking skill and experience to attempt to walk over steeper slopes.

**Method**

**Subjects**

We recruited 23 toddlers (12 girls and 11 boys) by telephone from a subject pool of parents expressing interest in developmental research. All children were within 1 week of their 14-month birthday ($M = 14.01$ months), were able to walk 10 feet independently, and had never descended a slide independently. Most children were white, middle-class, and lived in the Emory University area. They wore play clothes and rubber-soled shoes for the experimental session. One child failed to contribute usable footprint sequences, and two additional children failed to complete the session because of fussiness.

**Apparatus**

We constructed a wooden walkway with an adjustable slope to present children with different affordances for locomotion. Two end segments (83.0 x 72.0 x 4.3 cm) were attached to a middle segment (79.5 x 91.0 x 4.3 cm) with dowel hinges. One end rested permanently on a 71-cm-high platform. The other end rested on one of five interchangeable platforms. These platforms were 71.0, 55.2, 39.9, 25.5, or 12.5 cm high, allowing the middle part of the walkway to be flat or to slope 10°, 20°, 30°, or 40° from horizontal, as shown in Figure 1. A slope is essentially a right triangle, in which change in surface slant covaries with height of the hill or length of the supporting surface. Due to space limitations and the limited endurance of young infants, we kept the length of the slope constant and allowed slant to covary with height. Thus, vertical distance from beginning platform to ending platform increased with surface slant (0 cm for the horizontal walkway, 15.8 cm at 10°, 31.1 cm at 20°, 45.5 cm at 30°, and 58.5 cm at 40°), while the total horizontal length of the walkway remained relatively constant (from 213.7 to 235.0 cm). Vertical distance from the surface of the walkway to the floor was greatest for the shallower slopes and when the walkway was flat (73.3 cm). Wooden poles at the four corners of the platforms provided children with support. Protective netting stretched between the poles along the sides of the platforms. The surface of the walkway was covered with a carpet to provide traction and a cushion against possible falls.

**Procedure**

First, toddlers were placed on the walkway when it was completely flat. After exploring the nets, poles, and carpeted surface, they walked back and forth several times to a parent to accustom them to the elevation of the walkway and the experimental task.

**Trials on slopes.**—Next, toddlers were encouraged to go once up and once down each of the four slopes for a total of eight trials. Because pilot research indicated that children and parents become distressed when slopes are presented in other orders, we presented children with slopes in increasing increments from 10° to 40°. Half of the children went up and then down each slope, and half went down and then up. All children attempted ascent of the 40° incline, indicating that they had not become fatigued over the course of testing. An experimenter stood the children at one end of the walkway. Parents at the far end of the walkway urged their children to come up or down to get some dry cereal, without telling them how to navigate the slope. Parents refrained from cautionary comments, and if infants asked for help, they were directed "to take their own self up or down the hill." An experimenter followed alongside the walkway to provide protection if necessary. Trials ended either when subjects completed traversal or after a 60-sec latency. All trials were videotaped with the camera perpendicular to the length of the walkway.

**Measures of action capabilities.**—Next, children reclined on the horizontal walkway while we measured leg length from pelvis to ankle to determine whether toddlers with longer legs also took longer steps (Scrunton, 1969). Finally, measures of walking skill were collected from footprint sequences in the hallway outside the playroom. Fifteen children contributed two sequences to assess consistency of gait across consecutive trials. We placed inked moleskin tabs on the midline of the bottoms of children's shoes (Boening, 1977). Children walked down a
long strip of paper (76.2 × 441.96 cm) to their parents, leaving behind a trail of footprints. Caut sequences were videotaped from a frontal view. Parents provided information on their children's prior locomotor experience. Walking experience ranged from 14 to 127 days (M = 68.05 days). Twelve toddlers had descended stairs independently by scooting backward feet first.

**Treatment of Data**

Videotapes of the eight trials on slopes were coded for latency to begin traversal, duration and type of exploration before starting onto slopes, mode of locomotion over the slopes, and success at completing traversal. Trials where children avoided traversal were excluded from analyses of latency. Time spent assuming the final posture and approaching the slope was subtracted out so that latency reflected only hesitation.

Haptic exploration included probing slopes with hands or feet. Accumulated duration of active touching (moving hands or feet over the surface, rocking at the brink, and touching while looking) was coded in real time with a computerized event recorder program. Exploration of different forms of locomotion was coded for frequency of discrete shifts in posture before starting onto slopes, with the criterion that each posture was sustained for at least .5 sec (e.g., standing to backing to standing to prone was coded as 3 shifts). Multiple shifts before leaving the starting platform would suggest that children explore alternative means of traversal.
We coded toddlers’ mode of locomotion from their initial posture at embarkation: walking upright (two or more steps on slope), climbing or crawling on all fours (both hands touched slope before both feet or knees), sliding in head first prone, sitting or back to positions, or avoidance (not embarking). We counted safely completed, independent traversals as successes, and trials requiring midslope adjustments (e.g., shifting from walking to crawling halfway up) or rescue from falling by an experimenter as failures.

A second judge independently coded latency, duration of haptic exploration, frequency of postural shifts prior to embarking, and mode of locomotion from six subjects to determine interrater reliability. Reliability was .99, .92, and .93, respectively. Raters agreed on 98% of the locomotion judgments.

Following previous research (Scrutton, 1969; Shores, 1980), we assessed gait measures only from the middle sections of each footprint sequence where children had hit their stride, presumably achieving steady state velocity (Breniere, Bril, & Fontaine, 1989). At least four prints from each foot were analyzed from each sequence. As illustrated in Figure 2, footprints were assessed for: (1) step length (distance from heel strike of one foot to heel strike of the other foot), (2) step width (distance between feet), and (3) foot rotation (toe out or toe in from heel strike). Leg length was not correlated with right or left step length, so step lengths were not normalized. Right step length, step width, and right and left foot rotation were reliable across consecutive trials. Correlation coefficients were .71, .84, .77, and .91, respectively, all p < .001. Because left step length was unaccountably unreliable across consecutive trials, only right step length was used for further analyses. A paired t test showed no difference between right and left foot rotation, so mean foot rotation was used for further analyses.

RESULTS AND DISCUSSION

There were no effects for trial order (up or down first), so this factor was excluded from all analyses below.

Perceived affordances.—We assessed perception of affordances by toddlers’ mode of locomotion and success at completing traversal. Deliberate shifts from walking to more stable climbing and sliding postures before embarking would indicate that toddlers perceive affordances. Overall, there were large differences between ascent and descent, and between slopes. As illustrated

![Diagram of gait parameters](https://example.com/diagram.png)

**Fig. 2.**—Calculation of spatial gait parameters from footprint sequences
by the height of the bars in Figure 3, some toddlers avoided descent but virtually none avoided ascent. Eleven toddlers avoided descent on at least one trial, but only two avoided descent of every slope, and six descended slopes after avoiding on earlier trials. As shown by the black bars and thick stripes in Figure 3, more toddlers tried to walk up 10°, 20°, and 30° slopes than tried to walk down (tests between proportions attempting up vs. down: 10°, Z = 2.86; 20°, Z = 2.38; 30°, Z = 2.56; all p's < .009). As indicated by the striped bars in Figure 3a, children overestimated their ability to walk and climb up slopes. Slips and falls were common during ascent, but mishaps were uneventful, and children were always able to safely catch themselves: paired t test comparing steepest slope attempted to walk up (M = 22.61°, SD = 10.96°) versus steepest walking success (M = 12.17°, SD = 12.04°), t(22) = 4.75, p < .001; paired t test comparing steepest slope attempted to climb up (M = 34.78°, SD = 13.77°) versus steepest climbing success (M = 18.26°, SD = 17.75°), t(22) = 4.16, p < .001.

In contrast, the striped bars in Figure 3b show that toddlers rarely fell while going down slopes. All but two toddlers safely completed every descent. These two subjects blithely walked down all the slopes, and had to be rescued at 20°, 30°, and 40°. As illustrated by the gray bars in Figure 3b, many children (18 overall) used sliding positions for successful descent. Thirteen used one sliding position exclusively (four subjects sitting, seven backward feet first, and two crawling or head first prone). The remaining five sliders used sitting positions on some hills and scooted backward down others. Of the 12 toddlers reported to back down stairs, eight backed down at least one slope. Of the 11 toddlers who never backed down stairs, four used this position for the first time on slopes. A test between propor-

![Toddlers' Attempts to Ascend Slopes](image)

![Toddlers' Attempts to Descend Slopes](image)

**Fig. 3.** Toddlers' attempts to (a) ascend and (b) descend slopes. The empty space above the bars indicates avoidance. Solid bars indicate success and striped bars indicate failure in toddlers' starting position. Black bars and thick stripes indicate attempts to walk over slopes. Gray bars and thin stripes indicate attempts to climb or slide over slopes.
tions approached significance (Z = 1.49, p < .068), suggesting that prior experience scooting backward down stairs may influence children's choice of sliding positions on slopes.

Latency.—Toddlers' latency to begin traversal followed these same patterns (Fig. 4). There were no differences in children's hesitation to ascend slopes regardless of whether they tried to walk up (M = 1.64, SD = 1.86) or climb up (M = 4.54, SD = 9.65), paired t(18) = −1.288, p > .10. In contrast, children hesitated before sliding down hills (M = 17.44, SD = 17.52), but not when walking down (M = 4.22, SD = 6.12), paired t(11) = −2.71, p < .05. An ANOVA (up/down × slope) on latency to begin traversal showed a main effect for direction, F(1, 152) = 15.93, p < .001, and a main effect for slope, F(3, 152) = 3.95, p < .009. Tukey HSD tests revealed differences at 10° versus 20° (p < .05). Variability was high, and the interaction between direction and slope was not significant, F(3, 152) = 2.08, p < .106. However, as illustrated by Figure 4, toddlers tended to hesitate longest before starting down 20°, where visual information specifying affordances for walking may be more ambiguous.

Exploratory activity.—We analyzed children's exploratory activity to determine how they gathered information for affordances (Fig. 5). Children performed two types of haptic/proxioceptive exploration before starting onto slopes: rubbing or patting slopes with hands or feet, or standing at the brink and rocking back and forth over their ankles. Overall, touches ranged from 0 to 7.30 sec for ascending trials, and from 0 to 39.48 sec for descending trials, but were generally of very short duration (for ascent, M = .29 sec, SD = .10 sec; for descent, M = 2.14, SD = .57). These low values are partly due to our stringent coding criterion, which included only active touches. Eighteen toddlers engaged in some touching; three subjects before ascent only, nine before descent only, and six before both. A repeated-measures ANOVA (up/down × slope) showed a main effect for direction, F(1, 22) = 7.81, p < .011, and a trend for slope, F(3, 20) = 1.77, p < .087. There was an interaction between direction of traversal and slope, F(3, 66) = 2.78, p < .048. Tukey HSD tests indicated differences before descent at 10° versus 30° and 20° versus 40° (p < .05). These results suggest that children explored surface slant and frictional properties on 10° and 20° when affordances for walking were least apparent visually (these slopes appear to be closest to the limits of toddlers' actual walking ability), and when the consequences of a misstep were more severe (during descent).

We assessed toddler's exploration of alternative means of locomotion by frequency of postural shifts before leaving the starting platform (Fig. 6). When children walked up or down slopes, they never shifted to a different position before starting onto the slope and never appealed to adults for help. When they climbed on all four up slopes, they quickly shifted from standing to quadruped and rarely appealed for help. In contrast, when they slid down or avoided descent, they often tried out several discrete postures and made frequent appeals for help. Overall,

**Fig. 4.—Toddlers' latency to begin ascent and descent of each slope. Trials where children avoided traversal were excluded.**
on ascending trials, frequency of shifts in posture ranged from 0 to 3 ($M = .45, SD = .65$). On descending trials, the number of shifts ranged from 0 to 8 ($M = 1.51, SD = 1.84$). A repeated-measures ANOVA (up/down x slope) on frequency of shifts in posture revealed main effects for direction, $F(1, 22) = 18.89, p < .001$, and slope, $F(3, 66) = 3.71, p < .016$. Tukey HSD tests revealed differences between $10^\circ$ versus $30^\circ$ and $40^\circ$ ($p < .05$). There was no interaction effect. These results indicate that toddlers explored different sliding positions for descent, when they perceived walking to be unsafe.

Relation between action capabilities and perceived affordances.—We expected children with more walking skill and experience to attempt to walk over steeper slopes. The steepest slopes each child attempted to walk up and down were used as dependent measures in two separate analyses. Days of walking, right step length, step width, and foot rotation were used as predictors. Viable cases (22) were distributed over too few slopes to warrant regression analyses, so slopes were clustered into dichotomous groups for stepwise discriminant analyses (Klecka, 1980). Differences in group means of the predictor variables are used to discriminate between groups and to calculate the probability of classifying new cases correctly. The stepwise method is especially useful for examining the partial effects of intercorrelated predictor variables.

The first analysis examined whether skill and experience were related to the steepest slopes toddlers attempted to walk up (13 subjects at $10^\circ$ or $20^\circ$ vs. nine subjects...

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**Fig. 5.—** Toddlers' haptic/proprcoceptive exploration before ascent and descent of each slope.
at 30° or 40°). A significant discriminant function correctly classified 77% of the cases (F = 8.13, p < .01). The stepwise procedure allowed only right step length to enter the equation. Although walking experience and right step length were moderately correlated (r = .44, p < .05), right step length retained its predictive power even when walking experience was forced into the equation first. Group means (25.88 cm vs. 29.88 cm) indicate that children with longer step lengths tried to walk up steeper slopes.

The second analysis examined the steepest slopes toddlers attempted to walk down (14 subjects at 0° or 10° vs. eight at 20°, 30°, or 40°). Discriminant analysis did not provide an equation that could predict attempts to descend. Thus, the results of the discriminant analyses found that right step length was the single best predictor of attempts to walk over slopes, but only for going up. Presumably, walking skill is also important for descent, but with only one trial per slope, and only two walkable inclines, these analyses are admittedly exploratory. However, the results do suggest that toddlers may perceive their own level of walking skill relative to the slope of a supporting surface.

In summary, results of Experiment 1 indicate that toddlers perceive affordances for walking over slopes. Subjects overestimated their ability to ascend, where consequences of falling were negligible. In contrast, they chose wide and appropriate means for descent, where falling is more dangerous. Haptic exploration and latency were highest before descending 10° and 20° slopes, where affordances for walking may be visually more ambiguous. Finally, toddlers actively explored alternative means for descent by testing out various sliding positions.

Experiment 2

Experiment 2 compared a younger group of crawling infants to the toddlers in Experiment 1. We essentially replicated the procedures used above to determine whether crawlers also perceive affordances for locomotion over slopes. Because of their presumably more stable, quadrupedal posture, we expected infants to crawl safely down 10° and 20° slopes (where most toddlers were wary of walking), but to be wary of descending 30° and 40°.

We were especially interested in crawlers' exploratory behavior. Are patterns of haptic exploration similar in crawlers and toddlers? All crawlers had the physical ability to use sliding positions for descent, and the task was designed to elicit these behaviors. Would they explore alternative means of locomotion by testing out various sliding positions before descent, or might new forms emerge serendipitously in the course of crawling down, as suggested by McGraw (1935)? Additionally, infants had different stable crawling styles—belly crawling, moving on hands and knees, or hands and feet. We expected that hands and knees/feet crawlers with greater postural demands would be more sensitive to affordances of slopes.

Method

Subjects

We recruited 28 8–9-month-old infants (M = 8.64 months, SD = .20 months) by telephone from a subject pool of parents expressing interest in developmental research. Eighteen were girls and 10 were boys, and all were able to crawl over the total length of the horizontal walkway without more than a 3 sec pause. All were inexperienced on slides and steep slopes. Most children were white, middle class, and lived in the Emory University area. One additional child fussed and refused to crawl on the walkway.

Apparatus and Procedure

The same walkway with adjustable slope was used as in Experiment 1, but it was covered with a softer carpet to prevent rug burn. Crawlers wore only diapers during the experimental session. First, measures of children's locomotor skill were collected on the flat walkway. Then children were presented with eight trials on slopes. As in Experiment 1, slopes were presented in increasing increments, and order of up/down first was counterbalanced. Crawlers were placed prone at the beginning of each trial. An experimenter followed alongside infants to provide protection if necessary. Twenty-five infants attempted ascent of the 40° slope, and the remaining three subjects (all belly crawlers) crawled over the flat walkway after avoiding ascent, indicating that infants had not become fatigued during the course of the procedure. All trials were videotaped with the camera perpendicular to the length of the walkway.

Measures of action capabilities.—We tested two aspects of locomotor skill: (1) components of sliding positions (sit alone, sit to prone, pivot 180°, sit and turn); and (2) characteristic crawling style. First, infants sat alone on the flat walkway facing their parents. They were encouraged to shift to
prone to get a toy (four times). Then children sat with their backs toward their parents and were encouraged to pivot 180° to reach their parents and a sounding toy (two times). Finally, children crawled back and forth four times along the horizontal walkway to reach their parents.

Treatment of Data

Measures of children's action capabilities were coded from videotapes. All children could sit alone, turn from sitting, shift to prone, and pivot 180°. Twenty-two infants used the same crawling style on all four trials on the flat walkway, and the six others used the same crawl on three trials, indicating stable modes of prone progression. Nine subjects crept along on their bellies, 16 crawled on hands and knees, and three on hands and feet. Parents reported children's locomotor experience, providing the date of crawling onset (10 feet in prone progression), for both belly crawling and hands and knees/feet crawling when applicable. Overall, total crawling experience ranged from 7 to 133 days. The nine belly crawlers had an average of 46.22 days of experience (SD = 15.85), and the 19 others had 35.21 days of hand and knee/feet experience (SD = 21.37) and 47.37 days experience total (SD = 31.28). Total crawling experience was approximately equal between the two groups because only nine hand and knee/feet crawlers passed through a preliminary phase of belly crawling. Two children were reported to have descended stairs by scooting backward feet first.

Similar to Experiment 1, videotapes were coded for latency, exploratory activity, mode of locomotion, and success at completing traversal. Haptic exploration was coded for accumulated duration of active touch with hands before starting onto the slope. Mode of locomotion included crawling on the belly, hands and knees, and hands and feet, as well as the various sliding positions. Any safely completed traversal was considered successful, regardless of whether infants shifted from one type of crawl to another midslope. An independent judge coded 25% of the trials. Correlation coefficients of interrater reliability for latency and haptic exploration were .99 and .96, respectively, and raters agreed on 97% of the mode-of-locomotion data.

Results and Discussion

There were no discernible effects for trial order (up or down first), so this factor was excluded from all analyses below.

Perceived affordances.—Overall, crawlers showed little ability to perceive affordances for locomotion over slopes (striped bars in Fig. 7). They tried to crawl up and down hills beyond their physical capability and slipped or fell: paired t test comparing steepest attempted ascent (M = 37.86°, SD = 6.86°) versus steepest successful ascent (M = 18.93°, SD = 6.85°), t(27) = 11.41, p < .001; paired t test comparing steepest attempted descent (M = 31.07°, SD = 9.94°) versus steepest successful descent (M = 11.07°, SD = 12.57°), t(27) = 5.29, p < .001. Most infants fell at least once crawling up (26 subjects), or down (23 subjects) slopes.

As illustrated by the height of the bars in Figure 7a, nearly every infant attempted to go up every slope. With each increment of slope, more crawlers shifted from their typical crawling style to a more upright crawling position as they pulled their upper body onto the hill (e.g., from belly to hands and knees; gray bars and light stripes). The slope itself appeared to facilitate these shifts because more body weight was supported by their legs. Despite shifting to hands and knees/feet, nearly all infants failed to get up 30° and 40° slopes. All infants safely caught themselves if they slipped or fell during ascent.

Crawlers fared worse on descending trials. As shown by the height of the bars in Figure 7b, most infants attempted to crawl down 10° and 20°, but many fell, indicating that balance is precarious despite crawlers' quadrupedal posture (striped bars). Although fewer attempted 30° and 40° slopes, nearly all that did fell headlong. Belly crawlers tumbled forward as an arm was caught under the chest, and hand and knee crawlers fell when their supporting arm collapsed. Two belly crawlers managed to slither headfirst down every slope safely in their typical crawling style (black bars at 30° and 40°). Five infants in total shifted from their typical crawling style to a more stable form of prone progression for descent (e.g., from hands and feet to hands and knees). Nonetheless, three of these subjects fell at 30° or 40° (light stripes). One additional subject shifted from hands and feet to hands and knees and crawled down 20° safely. But only one infant slid down headfirst prone without mishap. He was the only crawler to demonstrate deliberate and successful use of a sliding position (gray bars at 20°, 30°, and 40°).

The height of the bars in Figure 7b shows that avoidance increased over descending trials. Only two infants avoided de-
scent without prior falls. Avoidance in 13 infants may have been prompted by falling on previous trials (six subjects fell once, four fell twice, and three fell three times). Another 13 infants showed no avoidance, despite falling on previous trials (10 subjects fell three or four times). These results suggest that avoidance may be, but is not always prompted by falling, as well as by the steeply slanting surface and large drop-off. In contrast to visual cliff studies, many infants attempted descent of the 30° and 40° hills, despite the large vertical drop.

Latency.—Analyses of latency (Fig. 8) suggest the beginnings of wariness before descent, although all crawlers who hesitated eventually plunged down slopes and most fell. An ANOVA (toddlers/crawlers × up/down × slope) on latency revealed main effects only for direction, $F(1, 334) = 32.58$, $p < .001$, and slope, $F(3, 334) = 4.02$, $p < .008$; Tukey HSD tests indicated differences at 10° versus 20° ($p < .05$). There were two-way interactions between direction and slope, $F(3, 334) = 3.26$, $p < .022$; Tukey HSD tests revealed differences between up versus down only at 20° and 30° ($p < .05$) and between locomotor group and slope, $F(3, 334) = 2.93$, $p < .034$; Tukey HSD tests revealed differences only for toddlers at 20° versus toddlers and crawlers at 10° ($p < .05$), and no three-way interaction. An ANOVA on crawlers' latency (up/down × slope) showed only a main effect for direction, although the main effect for slope, $F(3, 182) = 2.33$, $p < .076$, and interaction between direction and slope, $F(3, 182) = 2.59$, $p < .054$, approached significance. These results suggest that infants in both groups were wary of descent; although the three-way interaction was not significant, toddlers hesitated longer before descending 20° and crawlers hesitated longer before descending 30° (compare Figs. 4 and 8).

Exploratory activity.—Crawlers performed two types of haptic/proprionicceptive exploration before starting onto slopes: rubbing or patting slopes with hands, or placing hands over the brink and rocking back and forth over the wrists. As shown in Figure 9, crawlers rarely touched slopes before ascent, but touching increased linearly over
descending trials. Active touch ranged from 0 to 3.95 sec before ascent ($M = .28$ sec, SD = .73 sec), and from 0 to 37.14 sec before descent ($M = 4.13$ sec, SD = 7.17 sec). Twenty-six crawlers engaged in some touching: 13 before descent only, and 13 before both ascent and descent.

A repeated-measures ANOVA (toddlers × crawlers × up/down × slope) showed a main effect only for direction, $F(1, 49) = 33.20$, $p < .001$, and two-way interactions between locomotor status and direction, $F(1, 49) = 4.08$, $p < .049$, and between locomotor status and slope, $F(3, 147) = 7.55$, $p < .001$. Most important, there was a three-way interaction between locomotor status, direction, and slope, $F(3, 147) = 8.34$, $p < .001$ (compare Figs. 9 and 5). Post hoc analyses showed an interaction between locomotor status and slope for descent, $F(3, 147) = 8.07$, $p < .001$, but no differences for ascent. Tukey's HSD indicated that crawlers touched longer than toddlers before descent of 30° and 40° slopes ($p < .05$).

Crawlers' increased touching before descending 30° and 40° may have been prompted by falling on previous trials, as well as the more obvious difficulties in traversal. Infants who avoided descent at 30° ($M = 10.64$, SD = 10.26) touched longer than infants who tried to go down ($M = 3.98$, SD = 5.13), $t(26) = 2.31$, $p < .05$, and infants who avoided crawling down 40° ($M = 10.95$, SD = 9.71) touched more than infants attempting descent ($M = 3.16$, SD = 3.27), $t(26) = 2.75$, $p < .02$. Despite the shorter durations of touching by infants attempting descent of these slopes, exploration was positively correlated with latency (correlation coefficients were, respectively, .70 and .77,

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**Fig. 8.—Crawlers' latency to begin ascent and descent of each slope. Trials where children avoided traversal were excluded.**

**Fig. 9.—Crawlers' haptic/proprioceptive exploration before ascent and descent of each slope.**
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all p's < .001). Thus, crawlers actively explored slopes during the time they hesitated, even if they plunged downward and fell.

In contrast to toddlers, crawlers never explored alternative means for descent before starting down slopes. Although every baby had the physical ability to scoot backward feetfirst down slopes (assuming a prone position and pivot 180°), no crawlers tested this position before descent. As McGraw observed, moving backward toward a goal appears to be a late-developing phenomenon. Similarly, nearly every infant demonstrated the ability to shift from prone to sitting, but none appeared to realize that such a position would be ideal for sliding.

Relation between action capabilities and perceived affordances. We examined infants' crawling skill and experience for effects on perception of affordances. Nearly every crawler tried to go up every slope, so ascending trials were not analyzed. The dependent measure was the steepest slope infants tried to go down (two subjects at 10°, six at 20°, seven at 30°, and 13 at 40°). Predictors were typical crawling style (belly vs. hands and knees vs. hands and feet) and total days of crawling experience. A chi-square test showed that crawling style was distributed evenly over the four slopes, χ²(6) = 4.76, p > .10. On average, infants attempting only 10° or 20° had more total crawling experience than infants who also attempted 30° or 40° slopes (10°, M = 55.50 days, SD = 14.85; 20°, M = 64.50 days, SD = 34.38; 30°, M = 26.86 days, SD = 15.98; 40°, M = 43.54 days, SD = 24.71). However, variability was high, and a comparison between 10° and 20° versus 30° and 40° was not significant, t(26) = 1.99, p < .10. In contrast to results obtained with crawlers on the visual cliff (e.g., Bertenthal & Campos, 1984), crawling experience was not strongly related to wariness of descending slopes.

In sum, Experiment 2 showed that, in contrast to toddlers, crawling infants were less able to guide locomotion safely over slopes. Crawlers' average ratio of success to failure over descending trials was 3:0; crawlers' was 1:2. Crawlers overestimated their ability to both ascend and descend slopes, and falling was common on every trial. Haptic exploration, latency, and avoidance were highest before going down 30° and 40° slopes, but could have been prompted by prior falls as well as by the more apparent difficulties for locomotion. None of the crawlers investigated alternative means to descend slopes, although every infant had the physical ability to slide downward feetfirst. Only one infant deliberately shifted from crawling to sliding down headfirst to complete descent safely.

General Discussion

In these experiments, infants were faced with independent locomotion over steep slopes. Children in both locomotion groups attempted to go up every slope with little prior exploration or hesitation, regardless of failure on previous ascending trials. The consequences of perceptual errors were negligible, and thus it was difficult to determine whether infants really intended to reach the summit in their starting position, or attempted ascent in a more playful exploratory manner. Both crawlers and toddlers appeared to gauge their ability to ascend slopes by actually attempting traversal, a sort of "learning by doing," as McGraw (1935) had observed.

However, falling was more aversive during descent, providing a more rigorous test of infants' perception of affordances. Most toddlers shifted from walking to sliding positions before starting down slopes, and falling was extremely rare. Toddlers' latency and haptic exploration were highest before descending the 10° and 20° slopes, where visual information for affordances for walking may be more ambiguous. Toddlers explored various sliding positions by testing them out before starting down slopes. These "tests" had a concerted, goal-directed quality, as if searching for alternative means to achieve a desired outcome. Although toddlers may have perceived affordances based solely on the height of the slopes rather than surface slant, it is likely that both properties were important. We are currently conducting research to disentangle the respective roles of surface slant and height for toddlers' perception of affordances of slopes.

In contrast to toddlers, most crawlers plunged down slopes headfirst and many fell. This is a very robust and interesting finding indicating that infants learn much about affordances for locomotion between crawling and walking from 8.5 to 14 months of age. Did crawlers simply fail to perceive the affordances of slopes? If so, what were they learning when they tried to crawl and fell, or as they hesitated and touched the sloping surface? What factors might drive the developmental progression?

Although 30° and 40° slopes had a large
vertical drop, a higher proportion of crawlers attempted descent than are reported to cross the deep side of a visual cliff (e.g., E. J. Gibson & Walk, 1960). Although Bertenthal and Campos (1984) suggest that wariness of heights is related to days of crawling experience, our findings did not provide strong support for this claim. An alternative explanation is that young crawlers are less attentive to their own postural stability than toddlers, who may be responding to the additional demands of balancing on two feet. Infants who avoided crossing a visual cliff using their own powers of balance went over it in a mechanical baby walker that reduced postural demands (Rader, Bausano, & Richards, 1980). Thus, infants may begin showing avoidance on slopes after walking onset, when posture becomes more unstable. A third explanation is that young crawlers are most sensitive to whether a supporting surface has a continuous visible texture. A visual cliff has an abrupt discontinuity in visible surface texture, and a slope has a continuous gradient. E. J. Gibson and Schmuckler (1969) found that infants who avoided a typical visual cliff eventually crawled over it when a net was stretched beneath the Plexiglas, although the floor was still visible far below. Thus, crawlers may have attempted descent because they could see a continuous surface stretching in front of themselves.

It seems probable that crawlers could detect differences between the slant and height of the four slopes, especially considering their differential exploratory behavior on descending trials. On the sloping walkway, haptic/proprioceptive and visual information were congruent (rather than conflicting as on the visual cliff), so that infants could explore the surface effectively in either modality. In other experiments, newborns differentiated surface slant of objects visually (e.g., Slater & Morrison, 1985), and infants showed differential avoidance behavior when the height of a visual cliff was varied (e.g., Sorce, Emde, Campos, & Klinnert, 1985; Walk, 1966).

What were infants perceiving as they peered down slopes and touched the surface? Crawlers may be sensitive to properties of slopes yet not perceive this information relative to their own physical capabilities (e.g., arm strength, postural stability, interlimb coordination). That is, infants may have detected information about slant, height, and texture of slopes without perceiving these properties relative to self. Thus, the developmental progression might involve learning to relate properties of slopes to one's own locomotor capabilities. A second possibility is that rocking the hands at the brink of a slope or patting or rubbing the surface may yield information specific to those actions without automatic transfer to the different constraints of crawling downhill. Perhaps crawlers did perceive properties of slopes relative to self, but must learn to generalize information obtained from exploratory actions to locomotion down slopes. A third possibility is that crawlers might have perceived properties of slopes relative to their ability to crawl down them, but information was poorly differentiated, resulting in a high rate of perceptual error on the range of slopes tested. That is, somewhere between 40° and 90° (a sheer drop-off) crawlers might have perceived affordances more accurately. By this account, the developmental progression involves a process of differentiation, so that perception of affordances becomes increasingly geared in to actual locomotor abilities by 14 months. The results do support such a developmental progression for haptic exploration. Touching the slope appears to be a first step in detecting information for affordances, but begins with long, ineffectual touches on 30° and 40° slopes (much steeper than infants' actual limits for crawling down) and becomes more efficient and more fine-tuned to children's own level of locomotor skill by 14 months (when infants touched more at 10° and 20°).

Despite their ability to perform all the component movements for sliding backward feetfirst or in a sitting position, crawlers never deliberately used these positions for descent. Most important, crawlers never explored these alternative means for descent, suggesting that this type of exploratory activity develops later than haptic exploration. Sequencing locomotor skills and using them as a means toward an end may depend on abilities not yet developed in young crawling infants (Piaget, 1952; Willats, 1989). Bruner and Kosowski (1972) suggested a similar explanation for infants' behavior when presented with large versus small balls. Two-month-olds showed differential behavior when presented with small balls (clasped hands at midline), but did not reach for them. The authors suggested that infants were sensitive to the size of the balls but could not sequence the movements necessary to reach for them. Although means-ends relations have not been studied directly in a
Locomotor task, Lockman (1984) found that infants reached around a barrier to retrieve a toy, but did not crawl around it to achieve the same ends. These results suggest that exploration of alternative means may be quite task-specific in infancy, appearing first in tasks involving object manipulation and only later in tasks involving locomotion.

Alternatively, young crawling infants may not yet realize that a supporting surface stretches behind them when they cannot see it. In our slope task, parents provided a continuous stream of verbal encouragement, and rattled toys throughout the trials, so crawlers' failure to turn their backs toward the goal was not due to an inability to remember the end point. As suggested by research with a visual cliff, young crawling infants may rely primarily on visual guidance for locomotion, making it more likely for them to keep their eyes directed toward the ending platform. In any case, the psychological implications of why moving backward toward a goal develops so late are deserving of further research.

What were crawlers learning when they tried to descend slopes and fell headlong? Half of the infants avoided 30° and 40° slopes after falling on previous trials, but half plunged down every slope despite prior falls. Their attempts might reflect clumsy efforts to explore possibilities for crawling, a sort of learning by doing as in ascending trials. Is wariness of descent dependent on fear of falling? Although falling appeared to be mildly aversive, few crawlers lushed or cried before descent. Infants appeared to be frustrated rather than frightened when avoiding descent, similar to E. J. Gibson's observations of infants on the visual cliff or waterbed (Gibson & Walk, 1960; Gibson et al., 1987). However, because slopes were presented in increasing increments only, effects of trial order and slope were confounded. Future research is needed where slopes are presented in other orders.

Effects of locomotor skill and experience were not conclusive, but suggested that toddlers with more walking skill were more likely to overestimate their ability to walk up slopes. Although days of locomotor experience was positively correlated with measures of walking skill, gait measures were better predictors of toddlers' behavior on ascending trials. We found no strong evidence for differential effects of skill or experience on crawlers' behavior on slopes. As in other experiments (e.g., Bertenthal & Campos, 1984), measures of locomotor experience were based on parents' reports of crawling or walking onset. However, there are large individual differences in how much infants crawl or walk after their onset dates, and in incidents incurred (e.g., falling, frequency of exposure to different environmental properties). Locomotor skill may affect onset date and, conversely, locomotor experience may affect improvements in skill. Additionally, a third variable such as body proportions may affect both onset date and locomotor skill. Thus, objective measures of locomotor skill such as footprint sequences may be more reflective of underlying abilities than parental reports of locomotor experience. Our simple and straightforward gait measures appear promising, but further research is needed with smaller increments of slope, and more trials per slope. We are currently conducting experiments to determine actual crawling and walking "thresholds," which are compared to statistically independent measures of perceived affordances for locomotion over slopes, and to parents' reports of locomotor experience versus kinematic measures of locomotor skill on a flat surface (Adolph & Eppler, 1992; Adolph et al., in press).

Increase in slant and height of hills required transitions from infants' typical form of locomotion to more stable positions, but further study is needed to determine detailed biomechanical constraints on walking and crawling over slopes. The results of the present research, in conjunction with those of McGraw (1935) and Giacalone and Rarick (1985), suggest how the human body may be better suited for ascent than for descent. Walking up slopes requires the stance leg to extend, using concentric muscle actions, while the swing leg flexes deeply to clear the sloping surface. Placement of the swing foot is not critical for maintaining balance. Momentum is slow from step to step, and hands are well positioned to break a fall. Similarly, when crawling uphill on hands and knees, body weight is largely supported by the legs over a single joint, and the supporting arm is extended during swing phase.

In contrast, walking down slopes requires the stance leg to flex, using more demanding eccentric muscle actions, in order for the swinging leg to contact the surface. Forward momentum and placement of the swinging leg must be carefully controlled to prevent toppling downward. As slope increases, forces due to friction decrease and torques on the supporting limb increase. As slope height increases, downward accelerations...
tion also increases, unless controlled during each step by shortening step length and decreasing step velocity. Counteracting vertical acceleration during descent is especially important in light of Bril’s research on the development of walking (Breniere & Bril, 1988; Bril & Breniere, 1991). Acceleration of the center of mass is positive at heel contact in adults, indicating that experienced walkers propel themselves upward during single leg support. However, the vertical acceleration of toddlers’ center of mass is negative at foot contact, meaning that inexperienced walkers begin each step in the state of a dynamic fall, and have poor postural control during single leg support. Downward slopes aggravate this problem by increasing the negative value of the acceleration at foot contact. Similarly, when crawling down slopes, body weight is supported preciptously by a flexed arm, and forward momentum must be checked either by bracing the arms between movements or increasing the velocity of leg movements to keep the center of mass within the base of support. Most important, our results show that both crawling and walking were easier to manage during ascent and more difficult during descent, so that affordances for infants’ typical mode of locomotion were approximately parallel for both locomotor groups. Thus, the similarity in behavior during ascent and the developmental differences in infants’ ability to cope with descent are especially striking.

These experiments show that infants must learn about affordances for locomotion over sloping surfaces. The first step may be fine-tuning exploratory behavior — touching hills when visual information is ambiguous, exploring alternative means for descent, and only “learning by doing” when consequences of error are negligible. The results underline the need for experimental research on the generalization and specificity of skill learning in infancy.

References


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