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BRIEF REPORT

The Developmental Relationship Between Infants' Exploration and Action on Slanted Surfaces

MARION A. EPPLER
East Carolina University
KAREN E. ADOLPH
Carnegie Mellon University
TAMRA WEINER
Indiana University

This research provides converging evidence that infants use exploratory activity to differentiate slant around a horizontal axis before they relate information about slant to consequences for locomotion. In Experiment 1, 14-month-old toddlers walked down safe, shallow 10° hills and slid down or avoided risky, steep 36° hills when height of the hills was held constant. Results indicate that judgments were based on slant. In Experiment 2, 9-month-old crawling infants explored shallow 10° and steep 30° slopes differentially in a nonlocomotor task. Exploration was similar to previous locomotor research with full-size hills, even though crawlers plunged headlong over both shallow and steep hills in the earlier study.

slant perception slanted surfaces slopes exploration exploratory behavior crawling infants walking infants locomotion

This research was designed to test signposts in the development of slant perception. Previous research suggests that *sensitivity* to visual displays of slant appears early in infancy (e.g., Atkinson, Hood, Wattam-Bell, Anker, & Tricklebank, 1988; Bower, 1966; Caron, Caron, & Carlson, 1978, 1979; Slater & Morison, 1985; Slater, Morison, & Somers, 1988); visual/manual *exploration* of slant in depth appears midway through infants' 1st year (Adolph, Eppler, & Gibson, 1993; Hofsten & Fazel-Zandy, 1984); finally, after infants gain experience exploring slant and its consequences, ability to use information about slant to *guide action* appears last (Adolph, 1995; Adolph et al., 1993; Hofsten & Fazel-Zandy, 1984; Lockman, Ashmead, & Bushnell, 1984). These experiments had two aims: (a) to furnish independent evidence about whether exploration and discrimination of surface slant precedes crawling infants' ability to determine consequences of slant for locomotion; and (b) to verify the endpoint of this developmental progression by showing that walking infants can use information about slant per se to cope with locomotion over sloping ground surfaces.

Crawling and walking infants respond quite differently to downward hills (Adolph et al., 1993). When encouraged to descend 10°, 20°, 30°, and 40° slopes, 14-month-old toddlers walked down safe, shallow slopes and slid down or avoided steeper, riskier ones. Toddlers hesitated and touched more on shallow hills, focusing exploration near the limits of their physical abilities (i.e., the point/slope where they could no longer walk and had to switch to another means of maneuvering downhill). In contrast, 8.5-month-old crawling infants plunged indiscriminately down shallow and steep slopes alike, requiring rescue by an experimenter. Although the younger crawling infants also showed evidence of differential exploration of the slopes through increased latency and touching, their exploratory activity was not geared closely to the limits of their physical abilities. They did not begin exploring

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Correspondence and requests for reprints should be sent to Marion Eppler, Department of Psychology, East Carolina University, Greenville, NC 27858–4353.

until steeper increments, and they plunged down steep hills nonetheless. In sum, both groups of infants differentiated steep and shallow slopes through exploration, but only toddlers adjusted their downward actions to match the steepness of the hills. These findings suggest that infants may generate information about slant in depth via exploratory movements before they can use information about slant to judge consequences for locomotion.

However, two potential confounds belie the validity of this interpretation. First, in all previous studies of infants' locomotion over slopes, degree of slant covaried with height of the vertical drop-off (e.g., McGraw, 1935). In Adolph and colleagues' (Adolph, 1995; Adolph et al., 1993) research, steeper slopes presented a larger vertical drop-off between starting and landing platforms. It is possible that older walking infants judged possibilities for locomotion based on height of the drop-off rather than steepness of slope. Numerous studies with infants on a visual cliff indicate that older infants avoid an apparent vertical drop-off (e.g., Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978; Gibson & Walk, 1960; Walk, 1966; Walk & Gibson, 1961). Our first experiment addressed the height/slant confound to test whether 14-month-old walking infants can use information about slant per se to judge possibilities for locomotion down slopes.

The second problem concerns crawlers' apparent ability to differentiate slant by their exploratory activity. In Adolph et al.'s (1993) experiment with younger crawling infants, degree of slant and trial order were confounded. Infants encountered steeper 30° and 40° slopes after falling on previous trials at 10° and 20°. Thus, increased looking and touching on steeper hills may have resulted from the aversive effects of falling, rather than degree of slant. This was not a problem for the toddlers because they rarely fell.

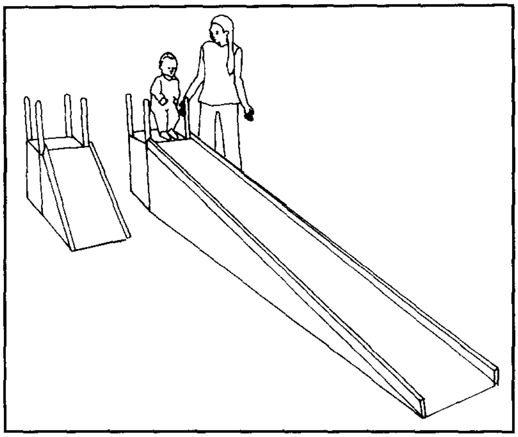
However, other research suggests that sensitivity and exploration of surface slant may precede the ability to determine the relevance of slant for guiding action. Although newborn infants discriminate line gratings slanting to the right versus left (Atkinson et al., 1988; Slater et al., 1988), sensitivity to pictorial two-dimensional displays does not mean that infants can use information about slant in depth to guide action. In fact, when infants begin to reach at age 5 months, they adjust their hand configurations to left/right slant of rods only after contacting the object, whereas by 9 months, they use information obtained from visual exploration alone to adjust hand orientation before touching the rods (Hofsten & Fazel-Zandy, 1984; Lockman et al., 1984). Apparently, visual discrimination of slant yields only rudimentary knowledge about object orientation. Only after months of experience reaching and manipulating objects do infants use information obtained from visual exploration to guide grasping.

Likewise, exploration of slant around the horizontal axis may appear prior to infants' ability to use this information to guide locomotion over slopes. Experiment 2 examines whether differential manual exploration of slopes precedes adaptive locomotor action on slopes in 9-month-old crawling infants. Because crawlers in the previous study fell at all four slope increments, simply changing the presentation order would not answer our question. We eliminated the aversive consequences of falling by presenting crawlers with an opportunity to explore steep and shallow slopes in a nonlocomotor task.

EXPERIMENT 1
Toddlers' Locomotion on Slanted Surfaces

The first experiment examined whether 14-month-old walkers can judge different possibilities for descending slopes based on information about surface slant alone. We addressed the confound between slant and height in previous studies by keeping height constant and allowing length of the slope to covary with slant (Figure 1). The diagonal length of the 10° slope was three times the length of the 36° one (318 cm vs. 94 cm, respectively), biasing the results conservatively against walking down 10°. The height of the vertical drop-off (55 cm) and diagonal length of the 36° hill (94 cm) approximated the dimensions of slopes used in previous research (53.5 cm and 91.0 cm, respectively), although the slopes used in this study were narrower (39.0 cm vs. 79.5 cm).

Eighteen 14-month-old toddlers (10 females, 8 males) were recruited from published birth announcements (*M* age = 427 days, *SD* = 5).



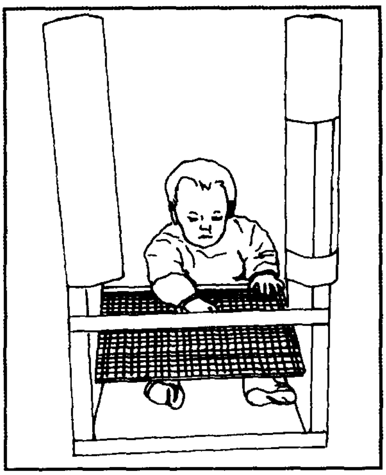


Figure 1. The steep and shallow hills used in Experiment 1 (top), and the rotating palm board used in Experiment 2 (bottom).

All infants could walk at least 10 steps independently and had no previous experience descending playground slides. Data from additional infants were excluded from analyses due to experimenter error (n = 1) and infant fussiness (n = 1).

As shown in Figure 1, toddlers were tested on a 10° slope versus a 36° slope. The two hills were placed 82 cm apart. Children descended toward the video camera located at the bottom of the hills. Infants were tested first on one slope, then the other in an alternating sequence for a total of four trials (10 infants received a 10-36-10-36 sequence; 8 received a 36-10-36-10 sequence). Infants began standing on the starting platform, while an experimenter followed alongside to ensure their safety. Parents sat on the floor at the bottom of the hill and encouraged their infants to come down by offering cheerios and toys. Trials were limited to 2 min if infants refused to embark. Coders scored infants' method of locomotion and accumulated duration of exploratory looking and touching. Interrater reliability (28% of the data) was high for both dependent measures (100% agreement for mode of locomotion; r = .91 for amount of exploratory looking and touching).

Results showed that toddlers can use information about slant alone to judge consequences for locomotion over slopes. Consistent with previous results (Adolph, 1995; Adolph et al., 1993), toddlers walked down the safe 10° hill (40% trials) and slid down or avoided the impossibly steep 36° hill (walked on 0% trials); test between proportions: z = 3.00, p < .05. On the largest proportion of trials, toddlers descended 10° by walking (40% trials); on remaining 10° trials, they crawled (17%), slid (26%), or avoided descending (17%). In contrast, walking (0%) and crawling (3%) down 36° was rare; on most 36° trials, infants slid down (63%) or avoided going (34%); $\chi^2(3, N = 72 \text{ trials}) = 51.40, p < .001$. Additional evidence that toddlers were not merely frightened by the height of the vertical drop-off was provided by infants' subversive attempts to scoot backward off the starting platform rather than heading down the slope toward their parents (6% trials at 10° and 36°).

Exploratory activity was also consistent with previous findings (Adolph et al., 1993). Toddlers engaged in more exploratory looking and touching on the shallow hill near the limits of their walking abilities than on the impossibly steep one. Toddlers touched the shallow 10° slope (M = 69% of each trial, SD = 24%) more than the steep 36° one (M = 55% of each trial, SD = 30%). A 2 (slant) × 2 (trial) repeated-measures ANOVA revealed only a significant main effect of slant, $F(1, 17) = 7.13, p < .02$. In sum, Experiment 1 indicates that toddlers can obtain information about slant via exploratory movements and use information about slant per se to choose appropriate methods of locomotion for descending slopes.

EXPERIMENT 2
Crawling Infants' Exploration of Surface Slant

The second experiment examined whether infants actually differentiate slant around a horizontal axis prior to judging consequences of slant for locomotion. We addressed the confound in previous research by giving crawlers an opportunity to explore surface slant (10° vs. 30°) in a nonlocomotor task, where there were no aversive consequences from falling to prompt their exploration. Infants were encouraged to press and probe a slanting palm board by shifting weight over their hands and generating torque at their wrists, simulating the types of exploratory touching movements that Adolph et al. (1993) observed in crawling infants in a locomotor task. We tested crawling infants at the same age of infants who had embarked indiscriminately down steep and shallow slopes in the previous experiment.

Eighteen 9-month-old crawling infants (7 females, 11 males) were recruited as in Experiment 1 (M age = 270 days, SD = 10). Data for additional infants were dropped from analyses due to experimenter error or equipment failure (n = 4) or infant fussiness or repeatedly crawling away (n = 5).

Infants sat in a booster seat in front of a large, rotating palm board (36.0 cm × 27.5 cm). When infants pushed on the palm board, it rotated downward from horizontal to 10° or 30° (Figure 1). When infants stopped pressing downward, the table top returned to a horizontal position via a weighted pulley mechanism hidden from the infants' view. The palm board was covered with a blue and white checkerboard pattern to provide varying optical texture gradients as the slope angle changed.

Sessions began with a brief familiarization period so that infants could learn to operate the palm board. Six infants warmed up on the 10° slant, and 12 on the 30° one. The experimenter placed a toy at the end of the horizontal palm board to direct infants' attention to the table top and to encourage touching it. After infants pushed three times, rotating the palm board through its full extent, they received four 60-s test trials that alternated between the two slants (10 received a 10-30-10-30 sequence; 8 received a 30-10-30-10 sequence). Each trial began with a toy at the far end of the table top; once the toy rolled off the board with the first downward push, it was not replaced. Infants continued to press and shift their weight over the palm board on all trials and rotated the board to its full extent on most pushes (an average of 77% of pushes on the shallow slope and 72% of pushes on the steep slope). Trials were videotaped from a frontal view, and coders measured accumulated duration of exploratory looking and touching with a computerized event recorder. Judgments of duration of exploratory bouts were reliable across coders for 22% of the data, $r = .85$.

Results showed that without requirements for locomotion, crawling infants displayed the same pattern of exploration with the slanting palm board that crawlers of the same age did on 10° and 30° hills in the earlier locomotor study (Adolph et al., 1993). They touched and looked longer at the steeper slope on its first presentation, and they used the same sorts of exploratory movements as infants in the locomotor task—pressing, shifting weight over the hands, rocking, banging, and rubbing. A 2 (slant) × 2 (trial) repeated-measures ANOVA revealed a significant interaction, $F(1, 17) = 4.74$, $p < .04$, but no main effects. The duration of exploratory looking and touching was longer for the 30° slant (M = 39.1 s, SD = 16.4) than for the 10° slant (M = 31.2 s, SD = 15.9), but only for the first trial, $t(34) = 2.95$, $p < .01$. Durations did not differ for the two slanting surfaces on the second trial (M = 31.5 s, SD = 14.1 for 10°; M = 29.0 s, SD = 17.9 for 30°), $t(34) < 1.00$.

It is possible that the steep 30° slope may have been more interesting to infants than the shallow 10° slope because of the increased torque required to move the table top and the larger motion as it returned to its horizontal resting position. Presumably, a similar situation existed in Adolph et al.'s (1993) locomotor task, where torque while rocking on the brink of the hill was greater for steep slopes and resulted in more visual flow and mechanical feedback to muscles and joints. The major difference between these two situations was self-motion over a hill versus motion of the hill. In both cases, crawling infants apparently found steep slopes to be more stimulating, because that is where they focused their attention and exploratory activity. Perhaps, in both cases, infants found it easier to discriminate steep slopes from a flat surface (flat ground and flat board) than to discriminate shallow slopes from a flat surface.

GENERAL DISCUSSION

Previous research suggested the rudiments of a developmental progression in slant perception. Sensitivity to visual displays of slant is followed by exploratory touching movements that generate information about slant. Exploration, in turn, is followed by the ability to relate information about slant to consequences for action.

Our initial aim was to verify two signposts in this hypothesized progression. We verified that young crawling infants demonstrate differential visual and manual exploration of slopes without aversive consequences for locomotion. Patterns of exploration and ability to discriminate horizontal slant extended beyond the single context of maneuvering over sloping ramps to a nonlocomotor task. We also verified that older walking infants can use information about slant per se to guide locomotion adaptively. These experiments provide converging evidence that infants use exploratory looking and touching to generate information for differentiating slant around a horizontal axis before they relate information about slant to consequences for locomotion.

This three-step sequence—sensitivity, differential exploration, then adaptive action—appears in two separate forms within the domain of slant perception. One involves perception of vertical slant and grasping objects, and the other involves perception of horizontal slant and maneuvering down hills. There is manifold evidence of visual sensitivity to slant in infants' first months of life; for example, sensitivity to vertical slant is evident in newborn infants (Atkinson et al., 1988; Slater & Morison, 1985; Slater et al., 1988). However, infants do not accurately adjust their hands to the slant of rods in anticipation of contact until after they have spent several months exploring and handling objects (Hofsten & Fazel-Zandy, 1984; Lockman et al., 1984).

By the age of 2 to 3 months, infants are able to discriminate horizontal slant (Caron et al., 1978, 1979), but they still do not apply this information to their actions. Midway through the 1st year, infants begin to explore slanted surfaces differentially by coordinated looking and touching (Adolph et al., 1993). Exploration, in turn, is followed later by adaptive action on slanted surfaces (Adolph, 1995; Adolph et al., 1993). Crawlers in Adolph et al.'s (1993) experiment plunged headfirst down steep and shallow hills alike, suggesting that exploration did not inform perceptual judgments about locomotion. Older 14-month-old toddlers also explored slopes differentially, but they made adaptive choices for locomotion (Adolph, 1995; Adolph et al., 1993).

These findings support and extend Gibson's (1988) proposed sequence of the development of exploratory behavior. Gibson argued that the onset of major motor milestones opens up new opportunities for learning. As new motor skills emerge, infants shift their attention and exploratory activity to properties of the environment relevant to guiding new actions. For example, the onset of independent locomotion corresponds to increased attention and exploration of the properties of ground surfaces. Our data suggest a further refinement—that exploratory activity and adaptively guiding action do not develop simultaneously. Although crawling infants do explore sloping ground surfaces, initially they do not use this information to guide their movement down the hills.

Why might knowledge about slanting surfaces not be related immediately to perceptual judgments about locomotor actions on slopes? Information obtained by using only part of the body (i.e., crawlers' hands and arms) may be adequate for differentiating surface slant but not for understanding the consequences of shifting the entire body (center of mass) onto a slanting surface. Young crawling infants may have to learn about the requirements for maintaining balance on different surfaces of support. Perhaps the repeated feeling of losing balance during the course of everyday locomotion helps to direct infants' attention to relevant features of the environment, namely the extent, rigidity, friction, and slant of ground surfaces in relation to proprioceptive information. With attention appropriately focused, infants have the opportunity to learn about the relationship between these environmental properties and their own ability to crawl over various ground surfaces.

Together, these studies point to a more general developmental trend. For example, visual cliff studies show a similar sequence of sensitivity preceding adaptive action. Heart-rate measures and placing responses suggest that infants discriminate the deep and shallow sides prior to crawling onset, even though they cross the deep side when they first begin crawling (Campos, Bertenthal, & Kermoian, 1992; Campos et al., 1978). Only after several weeks of crawling experience do infants behave adaptively, avoiding the drop-off. An important direction for future research is to assess whether this developmental sequence also occurs in other domains and to map the relation of exploratory behavior to guiding action.

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