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Development of Visually Guided Locomotion

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This article presents a developmental account of changes in the visual guidance of locomotion. In contrast to the impressive efficiency of adult locomotion, locomotor activity is not under prospective control at the onset of human mobility. Infants require extensive crawling and walking experience before responding adaptively to variations in the terrain. At the same time that they are learning to navigate in increasingly varied environments, their bodies and skills are rapidly changing. Learning generalizes from safe, flat ground to novel surfaces but it does not transfer to new methods of locomotion. We account for these patterns of generality and specificity of learning by focusing on the role of exploratory behavior in detecting threats to balance control.

As J. J. Gibson (1958/this issue) pointed out 40 years ago, locomotion involves more than muscles and biomechanics as animals walk over a laboratory treadmill or along a uniform path. Ground surfaces in a natural environment change in depth, slant, friction, and rigidity. The typical path is cluttered with obstacles and varies in extent. Terrestrial locomotion involves continual modification of ongoing activity, and it must be prospective and future-oriented, rather than merely reactive. Vision in many animals serves as a long-distance sense for controlling posture and steering so that movements may be selected and modified before balance is disrupted.

Adults of many species make visual control of terrestrial locomotion look easy. Human adults, for example, rotate their shoulders as they approach narrow door-

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ways (Warren & Whang, 1987), vary their step lengths to place their feet on target stepping stones (Warren, Young & Lee, 1986), and keep balance and steer as they jog along a simulated path (Warren, Kay & Yilmaz, 1996). Adults modify their ongoing movements with impressive efficiency, and researchers have identified potential sources of information that are sufficient for visual guidance—scaling to observers' eyeheight the geometric ratio of shoulder width to doorway width in the case of shoulder rotation (Warren & Whang, 1987), the rate of optical expansion of ground texture elements for the case of foot placement (Warren et al., 1986), and the rate and direction of visual flow patterns for steering (Warren et al., 1996).

In contrast to the rich literature on adult locomotion, relatively little research has examined visual control of locomotion during skill acquisition (Mark, Baillet, Craver, Douglas, & Fox, 1990; Vereijken, van Emmerick, Whiting, & Newell, 1993) or in the young of the species (see Adolph, 1997, and Adolph, Eppler, & Gibson, 1993b, for reviews). Developmental research is important for understanding processes of change. Visual guidance of performance is not always functional at the outset. Studying prospective control of locomotion as infants take their first faltering crawling and walking steps highlights the role of learning in skilled performance. In addition, infants' patterns of success and errors and their clumsy and slow exploratory movements reveal components of skilled performance that are not readily apparent in experts' behavior.

This article is divided into two sections. The first section presents evidence that visually guided locomotion is not functional at the start of mobility. In contrast to precocial (already locomotor) animals such as goats and chicks, in human infants, visually controlled locomotion is learned slowly over many weeks of crawling and walking. The second section describes a model of what infants may learn in the course of everyday locomotion and describes various functions of vision in controlling locomotion prospectively. Overall, the objective is to show that the developmental story both enriches and informs an account of prospective control of locomotion.

DEVELOPMENT OF INFANT LOCOMOTION

Human infants face special challenges for adaptive locomotion because development involves multiple methods of locomotion and dramatic changes in babies' bodies and skills. Typically, infants' first success at mobility is crawling, first on belly then on hands and knees, then walking sideways ("cruising") while holding onto furniture for support, and at last walking frontward without manual support. Most babies crawl and cruise for several months before they begin walking, and then toddle for several months before exhibiting characteristic features of adult gait such as reciprocal arm swing and heel strike at foot contact (McGraw, 1945). Despite infants' idiosyncratic and immature gait patterns, each method of locomotion shows rapid, dramatic improvements in the speed and consistency of its execution (e.g., Adolph, Vereijken, &

Denny, 1998; Freedland & Bertenthal, 1994; Vereijken & Adolph, in press). Most important, each method of locomotion involves different muscle groups, different patterns of interlimb coordination, different postural constraints, and different vantage points for viewing the environment. Infants progress from one method of locomotion to another against a backdrop of rapid changes in the size and proportion of their bodies. Their body dimensions become slimmer and more maturely proportioned. Their legs become longer relative to the torso and their center of mass lowers from the bottom of the sternum to slightly above the belly button (Palmer, 1944; Shirley, 1931; Snyder, Spencer, Owings, & Schneider, 1975).

With so much flux in infants' bodies and skills, the problem of adaptive locomotion is manifold in human development. Infants must gauge possibilities for locomotion relative to an action system that is itself changing from day to day. New methods of locomotion bring infants into contact with a widening array of novel surfaces (furniture, stairs, sandbox, cement sidewalk, etc.). The primary tools for perception—infants' eyes, extremities, skin and joint receptors and vestibular system—are dependent on the changeable motor system for their use. Peering at the ground, swaying over a jointed pivot, and probing the surface with a hand are different problems in crawling, cruising, and walking postures. Thus, yesterday's solution for coping with variable terrain may be inappropriate for today's level of locomotor skill. As described later, the developmental solution for acquiring adaptive locomotion in the midst of a changeable perception–action system and a variable environment may be long periods of learning about balance control.

The Visual Cliff

A well known paradigm for assessing visually guided locomotion in human infants is the "visual cliff." In the classic arrangement, a narrow starting platform divides a large Plexiglas™ table into two segments. The shallow side appears safe for locomotion because a visually textured surface lies directly beneath the glass. The deep side looks like a precipitous drop-off because the visually textured surface lies far beneath the Plexiglas™ on the floor of the crevice. Infants begin on the starting platform while their parents stand first at one side and then the other side of the table offering toys and praise as enticement for the babies to cross. A sharp discontinuity in visible texture marks the disparity in depth at the brink of the deep side. Visual texture gradients shift abruptly from the larger optic elements beneath infants' hands to the smaller optic elements at the base of the cliff. Head movements result in motion parallax specifying depth at an edge as infants peer over the brink. In E. J. Gibson and Walk's original studies, nearly every infant crawled over the shallow side and avoided the deep side of the visual cliff on their very first trials (E. J. Gibson & Walk, 1960; Walk, 1966; Walk & Gibson, 1961).

Despite multiple sources of visual information to specify the depth of the drop-off, visual guidance of locomotion at the edge of a cliff requires more than depth perception alone. Later studies showed that infants discriminate the shallow and deep sides of the visual cliff many months before they begin crawling (Campos, Bertenthal, & Kermoian, 1992; Campos, Langer, & Krowitz, 1970). Furthermore, adaptive guidance of locomotion at the brink of a cliff requires several weeks of crawling experience. In the original visual cliff studies, most infants were relatively old, experienced crawlers. In later replications, many younger, less-experienced infants crawled straight over the apparent drop-off (e.g., Rader, Bausano, & Richards, 1980; Richards & Rader, 1983). In some studies, more than 60% of infants crawled heedlessly over the brink (Bertenthal, Campos, & Barrett, 1984). Who were these dare-devils? Experiments using an age-matched control design indicate that the nonavoidant infants were the inexperienced ones who had just begun crawling. At the very same ages at testing (7.5–8.5 months), 60 to 70% of more experienced crawlers (M = 41 days of everyday crawling experience) avoided the visual cliff, but only 30 to 40% of less experienced crawlers (M = 11 days of experience) did likewise (Bertenthal et al., 1984). In a longitudinal study controlling for infants' everyday crawling experience, infants required 4 to 16 weeks of experience before they avoided crawling over the drop-off (Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978). One study points to the possibility that learning in a crawling posture does not transfer automatically to a less familiar upright posture. Infants who avoided the visual cliff when facing the drop-off from an experienced crawling position wheeled themselves straight over the drop-off when supported in an unfamiliar upright position in a mechanical baby walker (Rader et al., 1980).

Experience-related avoidance responses do not depend on specific experiences coping with the visual cliff. In fact, repeated testing on the visual cliff leads to attenuation of avoidance responses. Normally, visual information for a sheer drop-off is redundant with information obtained from touching. The visual cliff, however, violates these natural correlations. The Plexiglas™ renders it perfectly safe for locomotion, and haptic information specifies a sturdy supporting surface over the drop-off. Apparently, the haptic information for a sturdy surface can override the visual information for a drop-off. With repeated trials where infants touch the Plexiglas™ surface, infants are more, not less, likely to cross, despite the view of the floor far beneath their bodies (Campos et al., 1978; Eppler, Satterwhite, Wendt, & Bruce, 1997, Titzer, 1995). Thus, the learning that underlies visual guidance of locomotion on the visual cliff occurs during infants' everyday experiences traveling over the surfaces in their homes.

Slopes

Studies of infants crawling and walking down slopes offer further evidence that prospective control of locomotion is learned over many weeks of everyday locomotor experience (Adolph, 1995; Adolph, Eppler, & Gibson, 1993a; Adolph et al., 1993b;

Eppler, Adolph, & Weiner, 1996). These studies yield new evidence that the learning acquired during weeks of locomotor experience generalizes to novel surfaces but not to new methods of locomotion. In particular, knowledge obtained over weeks of crawling does not transfer over the critical transition to upright walking.

Slopes are an ideal venue for studying the development of visually guided locomotion for two reasons. First, slopes are novel. In contrast to the sheer drop-offs that are found in infants' homes, most infants have little or no experience viewing slanted ground or locomoting over slanted surfaces, especially declines slanting away from the line of sight. Transfer to novel surfaces would result if infants' locomotor experience on flat ground facilitates prospective control of locomotion in the novel slope task. Second, degree of slant can vary continuously allowing precise measurements of infants' current locomotor ability on slopes and the accuracy of their perceptual judgments. Specificity of learning would result if infants' experience in a familiar crawling posture did not transfer to a new method of locomotion after infants begin walking.

A longitudinal study of infants' locomotion over slopes. A longitudinal study was performed to assess how infants acquire prospective control of locomotion over novel terrain at the same time that their bodies and locomotor skills are rapidly changing (Adolph, 1997). This was the first study to observe adaptive motor control over the transition from crawling to walking. The longitudinal design controlled both for the duration of infants' everyday crawling and walking experience, and for infants' experience in the laboratory slope task. Fifteen experimental-group infants were tested on slopes every 3 weeks, from their 1st to last weeks of crawling and from their 1st to 13th weeks of walking. Fourteen additional control-group infants were tested at three matched sessions to control for practice effects on slopes in the laboratory: in their 1st and 10th weeks of crawling and in their 1st week of walking. At matched test sessions, age and everyday locomotor experience were similar across experimental and control groups; only practice on laboratory slopes differed. None of the children had experience on slopes outside the laboratory.

The basic plan was to compare infants' perceptual judgments on safe slopes to their judgments on risky ones. On safe slopes crawling or walking were possible with little chance of falling. On risky slopes, crawling or walking would result in falling. To descend safely, infants needed to use an alternative sliding position or avoid going altogether. The critical question was whether infants responded adaptively to risky slopes. If change in infants' judgments were due primarily to maturational factors, we would expect one smooth curve, with high error rates (frequent falls) in early test sessions when infants were younger and low error rates in later test sessions when they were older. If, however, infants' error rates showed two curves, decreasing over weeks of crawling and again over weeks of walking, we would have evidence that prospective control of locomotion is tied to experience with a particular method of locomotion. Similar patterns between experimental-group and control-group infants would indicate that learning generalizes from locomotion over safe, flat ground at home to locomotion over laboratory slopes.

Sloping walkway and procedures. As shown in Figure 1, infants encountered slopes on a large, carpeted walkway. Starting and landing platforms were flat, but the slope of the middle section of the walkway could be adjusted in 2° increments from 0 to 36°. The shallowest slopes were safe for all infants, and the steeper slopes were increasingly risky. In contrast to the visual cliff, the slope apparatus had no protective Plexiglas™. Thus, visual and haptic information were concordant on the slope apparatus rather than in conflict as on the visual cliff. Like a cliff, a slope has a disparity in depth between the top and bottom of the hill. However, a slope has a continuous surface rather than an abrupt discontinuity in visible surface texture. Visual information for surface slant and the depth of the drop-off is available from texture gradients and motion parallax. In addition, infants may obtain haptic information for the slant and friction of the surface by probing it with a hand or foot.

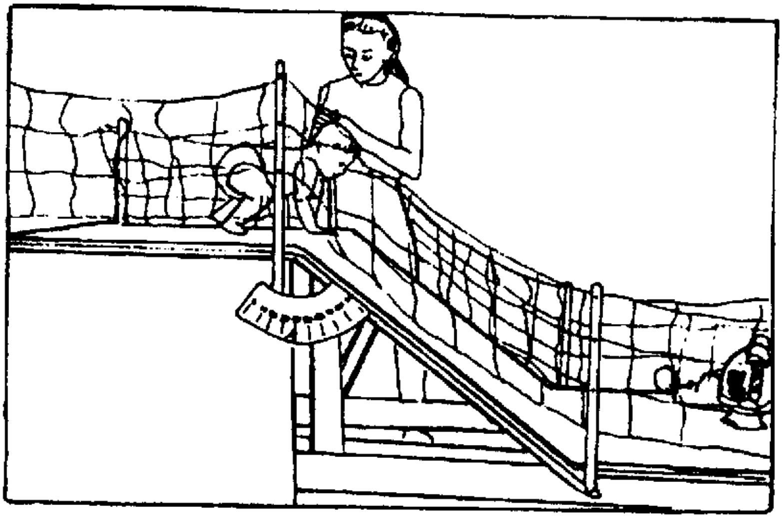

FIGURE 1 Walkway with adjustable slope. Infants began on flat starting platform. Parents stood at the far end of the landing platform. Experimenter followed alongside infants to ensure their safety. *Note*. From "Learning in the Development of Infant Locomotion," by K. E. Adolph, 1997, *Monographs of the Society for Research in Child Development*, 62(3, Serial No. 251), p. 42. Copyright 1997 by the Society for Research in Child Development, Inc. Reprinted with permission.

Infants began each trial on the flat starting platform. Crawlers started in a prone position, facing slopes from their typical crawling vantage point, and walkers started each trial in an upright posture, facing the hills from their typical walking vantage point. Parents stood at the end of a flat landing platform and offered toys, Cheerios™, and praise as enticements for their infants to come down. An experimenter followed alongside infants to ensure their safety if they began to fall.

In each test session, the experimenter used a classic psychophysical staircase procedure to identify the boundary between safe and risky slopes (described in Adolph, 1995). These slope boundaries provided a conservative estimate of each infants' crawling or walking ability on slopes as well as a way to compare the accuracy of infants' perceptual judgments with their current level of locomotor skill. Each trial was coded online as either a success (crawled or walked safely), a failure (tried their typical method but fell), or a refusal (slid down or avoided going). In general, steeper slopes were presented after successful trials and shallower slopes were presented after unsuccessful trials (failures or refusals). The process continued until converging on a slope boundary to a 67% criterion—the steepest slope where infants crawled or walked successfully on at least two thirds of trials, and where they were unsuccessful on at least two thirds of trials at the next 2° increment. In most protocols, boundaries were determined based on the ratio of successes to failures because infants were more likely to fall rather than refuse slopes at the next 2° increment. After identifying slope boundary, the experimenter presented two additional trials on the 36° slope to observe how infants coped with the steepest increment. Throughout the staircase procedure, easy 4° baseline trials were interspersed with the more challenging slopes to maintain infants' motivation.

At each test session, there was a wide range in infants' slope boundaries such that some infants could only manage very shallow hills and other infants could manage impressively steep ones. From session to session, each infant's body and skills changed. Over weeks of belly crawling, slope boundaries increased until some babies slithered down the steepest 36° slope. Most belly crawlers showed a decrement in slope boundaries when they switched from crawling on their bellies to crawling on hands and knees. Slope boundaries increased again over weeks of hands-and-knees crawling. All infants showed a sharp decrease in slope boundaries when they began walking upright and slope boundaries increased again over weeks of walking (see Figure 2). Infants who were better crawlers and walkers on flat ground (indexed by the size and speed of their steps) had steeper slope boundaries, supporting the validity of the estimates derived from the staircase procedure. Likewise, infants with slimmer, more mature body proportions had steeper slope boundaries.

The wide range in slope boundaries at each session and the change in boundaries from session to session underscores the importance of defining safe and risky slopes on an individual basis. A safe hill for proficient crawlers or walkers was risky for less skilled children. A risky hill one week might be safe the next week when lo-

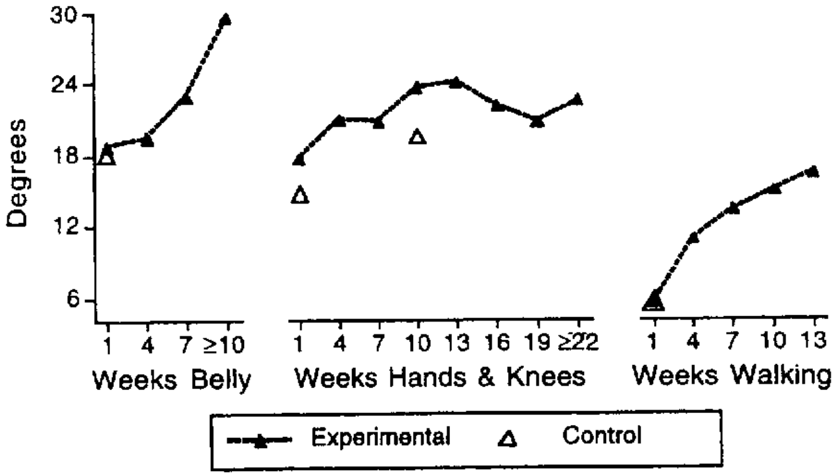

FIGURE 2 Change in slope boundaries over weeks of crawling and walking. Slope boundaries = steepest slope infants crawled or walked down successfully to a 67% criterion. *Note*. From "Learning in the Development of Infant Locomotion," by K. E. Adolph, 1997, *Monographs of the Society for Research in Child Development*, 62(3, Serial No. 251), p. 58. Copyright 1997 by the Society for Research in Child Development, Inc. Adapted with permission.

comotor skill has improved. A safe hill might become risky when infants switched from crawling on their bellies to crawling on their hands and knees or from crawling to walking.

The go ratio. The critical question was whether infants perceived the difference between safe and risky slopes relative to their changing locomotor skill. If infants perceived the hill to be safe, they should attempt it using their typical method of locomotion. If they perceived it to be risky, they should use an alternative sliding position for descent or avoid going. The penalty for error on risky slopes was falling downward and infants found it aversive.

A "go ratio" indexed the accuracy of each infant's judgments at each test session (described in Adolph, 1995, 1997). This measure is reported separately for safe hills shallower than boundary and for risky hills steeper than the infant's slope boundary. The go ratio was the number of trials on which infants attempted their typical method of locomotion (successes + failures) divided by the total number of trials (successes + failures + refusals). At the boundary slope, go ratios were .67 by definition, but the go ratio varied freely at all other increments of slope. For example, the go ratio would be 1 if infants simply used their typical method of locomotion and proceeded to go on every trial (all trials were successes and failures). Conversely, the go ratio would be 0 if infants always used an alternative sliding position or avoided descent (all trials were refusals). Successes were rare on hills steeper than infants' slope boundaries by definition, so that the go ratio on risky hills reflected largely the ratio of failures to refusals. Failures were rare on hills shallower than boundaries by definition, so that the go ratio on safe hills reflected largely the ratio of successes to refusals. Perfect judgments would be indicated by a go ratio that exactly matched the probability of success. Alternatively, infants could err on the side of caution with low ratios on perfectly safe slopes or err on the side of boldness with high ratios on impossibly risky slopes. Due to the nature of the staircase procedure, most of the trials on risky slopes were on hills slightly steeper (2–8°) than infants' slope boundaries. Thus, a low go ratio on risky slopes would be evidence for remarkably fine grained discrimination of slopes in the service of guiding locomotion.

Learning to cope with slopes. Infants' perceptual judgments provided strong evidence that prospective control of locomotion is learned and that learning is both general with regard to the ground surface and specific with regard to infants' crawling or walking posture. On safe slopes, infants' go ratios were near to 1.0 at every week of testing. Risky slopes held the interesting developmental story. There were three important results.

First, there were no differences between experimental-group infants, who had received hundreds of trials on downhill slopes over many weeks of testing, and control-group infants, who were tested only three times (see Figure 3). This finding indicates that learning generalized from experiences locomoting over safe, flat ground at home to locomoting down novel laboratory slopes. That is, learning did not depend on acquiring specific knowledge about slopes.

The second important result was that the impressive generalization across surfaces was matched by a striking specificity of learning across crawling and walking postures. As shown in Figure 3, infants' go ratios on risky slopes showed two learning curves, one over weeks of crawling and one over weeks of walking. In their 1st weeks of crawling, infants plunged headlong over the brink of risky slopes; the average go ratio on this group of hills was .68. Over weeks of crawling, falling on risky slopes decreased until the average go ratio was .11 by infants' last week of crawling. Surprisingly, there was no transfer from crawling to walking, and learning was no faster the second time around. In their 1st weeks of walking, infants attempted to walk down impossibly steep hills. The average go ratio was .66, just as high as in infants' 1st week of crawling. With weeks of walking experience, perceptual judgments steadily improved; the average go ratio decreased to .24 by infants' 13th week of walking. Apparently, infants had to learn

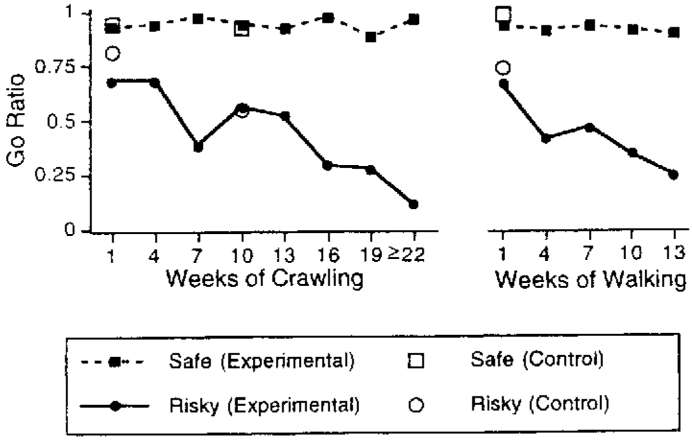

FIGURE 3 Go ratios on safe and risky slopes over weeks of crawling and walking. Go ratio = number of trials on which infants attempted their typical method of locomotion (successes + failures) divided by the total number of trials (successes + failures + refusals). Safe slopes = hills shallower than slope boundaries and the boundary slope. Risky slopes = hills steeper than slope boundaries. *Note.* From "Learning in the Development of Infant Locomotion," by K. E. Adolph, 1997, *Monographs of the Society for Research in Child Development*, 62 (3, Serial No. 251), p. 64. Copyright 1997 by the Society for Research in Child Development, Inc. Adapted with permission.

all over again how to distinguish safe from risky slopes in their new upright posture. In fact, infants showed no transfer from crawling to walking, even from trial to trial. When new walkers were tested at the steepest 36° slope in their old, familiar crawling posture, they slid down or avoided going. Moments later, when tested in their new, unfamiliar upright posture, the same adaptive crawlers walked straight over the brink and fell.

Finally, within sessions, infants' perceptual judgments on risky slopes were scaled to their locomotor ability. At every week of testing, infants were most likely to attempt the least risky hills slightly steeper than their slope boundaries (higher rate of failures) and least likely to attempt the most risky hills most remote from their slope boundaries (higher rate of refusals). For example, in infants' 1st week of crawling, the average go ratio on slightly risky slopes 8° steeper than slope boundaries was .74. The average go ratio on impossibly risky slopes 18° steeper than slope boundaries was .50. In infants' last week of crawling, these two ratios decreased to .15 and 0, respectively. Thus, even from the beginning, infants' judgments reflected differentiation of the stimulus information specifying possibilities for action, but discrimination improved dramatically with weeks of locomotor experience.

WHAT INFANTS LEARN

The evidence from cliffs and slopes presents a challenge for a developmental account of visually guided locomotion: What might infants learn from everyday locomotor experience that would account for this complex developmental pattern of transfer to novel surfaces but not to new methods of locomotion? Several possible accounts can be eliminated. Sensitivity to depth information precedes the onset of locomotion by several months (e.g., Campos et al., 1992; Yonas & Owsley, 1987), which means that immature depth perception cannot explain infants' lack of avoidance on cliffs and risky slopes during the early weeks of crawling. Infants are not merely learning to fear heights or the aversive consequences of falling because experienced crawlers' avoidance responses do not carry over to their 1st weeks of walking. Nor do infants need to learn to link aversive falling with particular surface properties. Falling in home accidents is unrelated to avoidance on the visual cliff or on slopes (Adolph, 1995, 1997; Scarr & Salapatek, 1970). In the laboratory, after falling over real cliffs or slopes, infants often attempt the same impossible cliff or slope moments later on the very next trial.

Infants do not need to acquire knowledge about a particular surface property in order to avoid aversive falls. Infants with no prior experience on slopes behave similarly to infants with frequent exposure to a wide range of slopes when groups are matched for everyday locomotor experience or for age. Most important, infants do not learn to pair a static concept of their own abilities with a particular surface property or to pair a particular surface property with a particular locomotor response. Infants' changing slope boundaries and recalibrated go ratios belie an explanation based on simple associative pairing. In fact, simple associative pairing would be maladaptive because infants' bodies and skills change from week to week and the everyday terrain is variable.

Balance Control

An explanation that can account for both transfer of learning to novel surfaces and specificity of learning across methods of locomotion is that experience promotes learning about balance control. In particular, everyday locomotor experience promotes learning to detect threats to balance and compensatory strategies for recovering balance when it is disrupted. To keep balance, infants must maintain their bodies within a region of permissible postural sway (Riccio, 1993; Riccio & Stoffregen, 1988). Infants will fall over if their body moves outside their base of support without sufficient muscle strength to pull themselves back into position. Visual, vestibular, and kinesthetic systems provide redundant information about the extent of swaying movements and the result of compensatory responses. Variations in the slope, the friction, or the compliance of the ground threaten infants' balance because the region of permissible sway narrows and infants' bodies move more rapidly toward the outer limits. Locomoting over a small drop-off or a gap in the surface of support requires infants to plant their limbs on the far side of the obstacle before exceeding their region of permissible sway. On an impossibly large cliff, of course, balance would be disrupted because there is no floor at all. In addition, a large disparity in depth at the edge of a cliff or steep slope violates the normal correlations between visual, kinesthetic, and vestibular information (Bertenthal & Campos, 1990). The resulting feeling of disequilibrium may alert infants that balance is threatened and prompt them to test their region of permissible sway.

To reduce postural sway, infants may attempt to minimize the optic flow associated with swaying movements (Warren, 1988). They can do this by stiffening their bodies, modifying ongoing gait patterns such as step length and velocity, generating compensatory movements more quickly, or, in extreme cases, switching to a different method of locomotion. Thus, an adaptive response at the edge of a risky surface means that infants obtained information online about their current region of permissible sway relative to surface properties. Adults must do likewise when they modify stance and gait to accommodate a changing region of permissible sway in a new pair of shoes, while carrying a load, or while locomoting over irregular terrain (Mark et al., 1990).

Posture-specific information for balance control and adjustment may generalize to new surfaces and across changes in locomotor skill within a particular posture because only the size of the sway-window changes, not the other parameters of the control system. The developmental shift from one method of locomotion to another presents a different problem. Infants' learning may be posture-specific because each gross motor skill represents a different balance control system with different relevant parameters. Crawling and walking, for example, involve different regions of permissible sway for different key pivots around which the body rotates (see Figure 4). These two postures also utilize different muscle groups for moving forward and for generating compensatory sway, different vantage points for view-

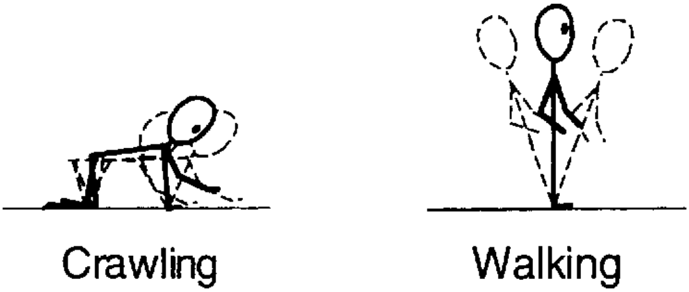

FIGURE 4 Regions of permissible sway for crawling and walking postures. In crawling, the key pivot around which the body rotates is the wrists. In walking, the key pivot is the ankles.

ing the ground ahead, different extremities for obtaining haptic information, different correlations between visual and vestibular information, and so on.

In a hands-and-knees posture, infants sway around the wrists, shoulders, and hips. Much of their body weight is supported on their relatively weak arms. Corrections for postural sway are limited by how far they can rotate around their wrists before falling forward. A crawler's vantage point is close to the floor and the hands and arms are used to obtain information from touching. In an upright posture, in contrast, infants sway around their ankles and hips. Body weight is supported by the legs over a smaller and more precarious base of support. Corrections for postural sway are limited primarily to rotations around the ankles (Stoffregen, Adolph, Thelen, Gorday & Sheng, 1997, Woolacott & Sveistrup, 1992). Toddlers' vantage points are elevated compared with that of crawlers and the feet and legs are used to obtain information from touching.

Exploratory Behavior and the Function of Vision

Exploratory activity provides the means for obtaining multiple forms of information about surface properties and the current status of the critical region of permissible sway. On slopes, for example, infants can obtain visual information about depth and slant from binocular disparity, changing visible texture gradients, and motion parallax. Touching movements at the brink of the slope provide information about slant and friction. Visual and mechanical information about infants' own postural stability is available from swaying movements as infants pause on the flat starting platform or peer over the edge (e.g., Bertenthal & Clifton, 1998; J. J. Gibson, 1958/this issue; Lee, 1993). Forward sway of the body is specified by a backward stream of texture elements in the optic array; backward sway of the body is specified by a forward stream of optic texture elements. The speed of the swaying movements is specified by the speed of the optic flow. Most touching movements on slopes involve rocking over the wrists or ankles with the hands or feet straddling the brink of the hill, so that torque and shearing forces provide information about infants' stability relative to the surface properties (Adolph, 1995, 1997). Changes in input to mechano-receptors in the joints and skin are concomitant with changes in the optic array.

The raw materials for obtaining information about ground surfaces and balance control are available long before infants become independently mobile. Discrimination of the relevant information appears first. For example, long before they can crawl, babies discriminate visual information for depth on the visual cliff (Campos et al., 1970) and for slant relative to the line of sight (Slater & Morison, 1985). Precrawling infants also discriminate visual and mechanical information for postural sway (Butterworth & Hicks, 1977; Hirschfeld & Forssberg, 1994). Differential, self-initiated exploratory activity appears next, as soon as infants have sufficient motor control to execute the movements. For example, 8-month-old crawling infants explore shallow (10°) and steep (30°) slopes differentially in both locomotor and nonlocomotor tasks. They press their hands against the sloping surface and rock back and forth about their wrists, all the while looking at their hands and the slope (Adolph et al., 1993a, Eppler et al., 1996). However, physiological sensitivity and adequate motor control to execute exploratory movements are not sufficient for prospective control of locomotion. Even though newly crawling infants explore shallow and steep slopes differentially, they fail to show any discrimination when asked to locomote over those same slopes.

The ability to use the relevant information for guiding locomotion appears last after a prolonged period of locomotor experience. In the longitudinal slope study, infants' exploratory activity showed discrimination of safe and risky slopes even in the 1st weeks of crawling when perceptual judgments were least accurate (see Figure 5a). Overall, exploratory activity became increasingly discriminating and efficient, paralleling improvements in infants' go ratios. In infants' 1st weeks of crawling, levels of latency and touching were highest and distributed over both safe and risky hills. Over weeks of crawling, latency and touching decreased and gradually became focused exclusively on risky slopes. In infants' 1st weeks of walking, latency and touching remained at low levels and continued to be restricted primarily

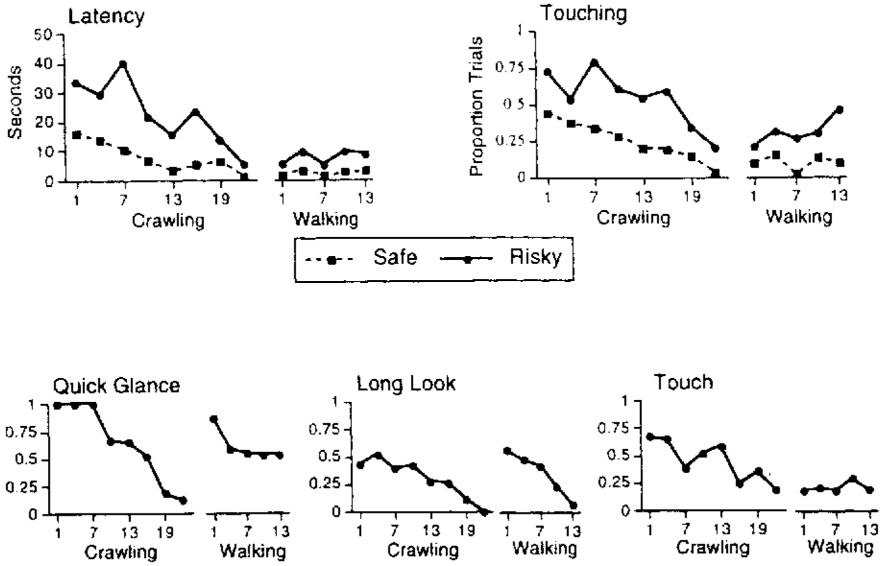

FIGURE 5 Exploratory looking and touching over weeks of crawling and walking. (a) Duration of latency and frequency of touching prior to starting down safe and risky slopes. (b) Go ratios on risky slopes after three types of exploration. *Note*. From "Learning in the Development of Infant Locomotion," by K. E. Adolph, 1997, *Monographs of the Society for Research in Child Development*, 62(3, Serial No. 251), pp. 71, 75. Copyright 1997 by the Society for Research in Child Development, Inc. Adapted with permission.

to risky slopes, then touching gradually increased. During the time that infants hesitated, they remained oriented toward the hill and the landing platform. Most touches occurred after several seconds of looking at the slope ($M = 6$ sec) and touches were always accompanied by looking at the surface or the limb.

At the same time that exploratory movements became more refined, they also became more efficient for supporting infants' perceptual judgments. Figure 5b shows a decrease in go ratios on risky slopes over weeks of crawling and walking after three types of exploration: trials where infants took only a quick glance at the hill (latency 1 sec, no touches), trials where infants engaged in prolonged looking accompanied by swaying and stepping movements on the starting platform (latency > 1 sec, no touches), and trials where infants engaged in coordinated looking and touching.

For experienced crawlers and walkers, vision may serve two functions: an initial long-distance probe for controlling ongoing gait patterns and a redundant confirmatory role for assessing balance control. The schematic diagram in Figure 6 illustrates how experienced infants may gather information online during a single trial. The first box in the diagram represents visual information as a first line of defense in prospective control of locomotion. Each subsequent box in the diagram represents additional sources of information so that visual information may be redundant with or complemented by mechanical information generated during swaying, stepping, and touching movements.

First, infants take a quick glance at the ground ahead. If the surface looks manageable, they continue with their current method of locomotion. Most of the trials on slopes were of this quick glance-and-go variety, where infants relied primarily on brief visual information for their perceptual judgments and started onto slopes within a second of their release onto the starting platform. Second, if a quick glance hints at something amiss, they hesitate on the starting platform and take a longer look. Prolonged visual exploration is accompanied by stepping and swaying movements that generate correlated visual and mechanical information for their region of postural sway. Third, if a long look suggests that the hill is risky, infants obtain additional information from coordinated looking and touching. Touching with rocking movements at the brink of the slope provides particularly useful information for controlling locomotion because infants test their region of sway on the questionable surface. Finally, if a touch suggests danger from falling, they select an alternative method of locomotion or avoid going.

The Origin of Exploratory Movements

Several studies have shown higher levels of exploratory looking and touching movements in inexperienced crawling infants compared with experienced toddlers (Adolph et al., 1993a; Eppler et al., 1996; E. J. Gibson et al., 1987). Both avoidant and nonavoidant crawlers showed visual exploration at the edge of a cliff (Rader et al., 1980). In contrast, walking infants' exploratory activity neatly mirrors their go

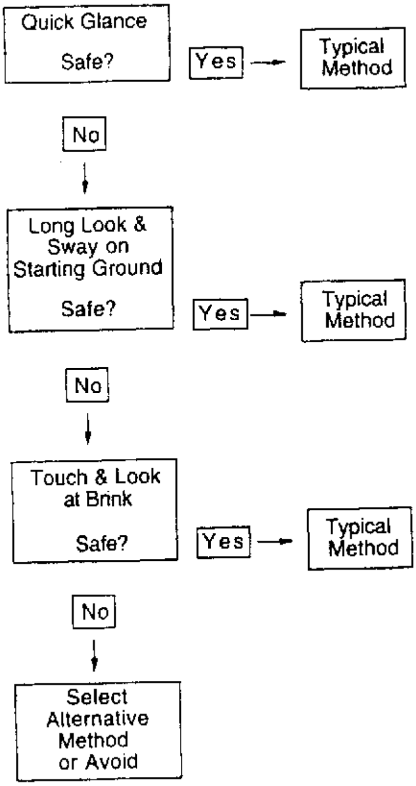

FIGURE 6 Schematic description of exploratory activity by experienced crawlers and walkers. Boxes represent a sequence of exploratory behaviors in a single trial.

ratios on risky slopes (Adolph, 1995). A puzzle arises as to why inexperienced crawling infants stop, look, and touch a potentially risky surface, but plunge onto it nonetheless. If knowledge of consequences prompted the exploratory behaviors, infants should have displayed more prudent responses. The answer to this puzzle may be found in the different constraints on newly developing locomotor skills.

When infants first begin crawling, most babies have weak arms and top-heavy bodies. Their heavy heads keep their eyes pointed toward the ground and their weak arms keep body weight distributed toward the legs. On flat, visually continuous ground, new crawlers' gait is punctuated by frequent pauses when they pat the floor and rock back and forth over their wrists, as though gathering energy for the next step (e.g., Adolph et al., 1998; Goldfield, 1989). Initially, newly crawling infants may execute the same looking and touching movements at the edge of slopes and cliffs that they do on flat ground due to the biomechanical constraints of their new quadruped posture. Crawlers could look at the floor, sway to and fro, and generate torque around their wrists without understanding the relevance of these movements for guiding locomotion. In many tasks, infants show sensitivity and differential exploratory behavior to surface properties prior to showing adaptive responses (Adolph, 1997; Bertenthal & Campos, 1990; Eppler et al., 1996). Useful exploratory movements may enter infants' repertoires serendipitously in the course of acquiring a new motor skill, and later, after sufficient experience, the same movements are used intentionally to obtain information for controlling a motor response.

Biomechanical constraints also may explain the low levels of exploration in infants' 1st weeks of walking. In an upright posture, rotating the head downward to look at the floor shifts infants' center of mass forward, threatening their already precarious balance. New walkers have difficulty keeping balance on one leg, so they plant their swinging leg as quickly as possible (Bril & Breniere, 1992). On flat safe ground, new walkers' gait is a series of stiff and jerky transitions between long double support periods and brief periods when one leg is in motion. There is no serendipitous halt at the brink of a novel surface. Rather, toddlers' exploratory swaying and touching movements likely reflect intentional efforts to obtain additional information after a brief glance at the ground ahead.

SUMMARY

For infants, the problem of prospective control of locomotion may be straightforward—how to go from one place to another without falling over. For researchers, the problem seems daunting. At the same time that infants acquire adaptive mobility, their bodies, skills, and environments undergo rapid change. Infants require several weeks or months of everyday locomotor experience before responding adaptively to risky surfaces and their learning does not transfer to unfamiliar postures. These data point up an issue that is ignored in the adult literature: How does any animal guide locomotion adaptively when the biomechanical constraints on balance control are continually changing? Possibly, the rapid changes in infants' bodies, skills, and expanding environments prevent them from learning particular behavioral solutions that would prove maladaptive in the long run. The changeable nature of locomotor development may serve to ensure that infants acquire knowledge at just the level of generality and specificity that they need.

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