Learning and Development in Infant Locomotion

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The traditional study of infant locomotion focuses on what movements look like at various points in development, and how infants acquire sufficient strength and balance to move. We describe a new view of locomotor development that focuses on infants' ability to adapt their locomotor decisions to variations in the environment and changes in their bodily propensities. In the first section of the chapter, we argue that perception of affordances lies at the heart of adaptive locomotion. Perceiving affordances for balance and locomotion allows infants to select and modify their ongoing movements appropriately. In the second section, we describe alternative solutions that infants devise for coping with challenging locomotor situations, and various ways that new strategies enter their repertoire of behaviors. In the third section, we document the reciprocal developmental relationship between adaptive locomotion and cognition. Limits and advances in means-ends problem solving and cognitive capacity affect infants' ability to navigate a cluttered environment, while locomotor development offers infants new opportunities for learning.

Key Words: Infant, Locomotion, Affordance, Perception-Action, Crawling, Walking, Means-Ends Problem Solving

How Infants Move

Traditional View

For more than 100 years, researchers have posed the question of how infants move (e.g., Ames, 1937; Burnside, 1927; Trettien, 1900). Locomotion is one of the great coups of infancy. The advent of independent mobility marks the transition from helpless newborn to independent agent. How do infants triumph over gravity so as to pull their bodies from the ground and power up to go somewhere?

The traditional answer has two parts. The first part addresses what movements look like at various points in development. In an attempt to minimize extraneous environmental factors and varied task demands, researchers encourage infants to crawl and walk repeatedly over a flat, uniform surface at a steady pace. A century of clever and increasingly sophisticated technologies has produced precise documentation of the timing and coordination of infants' locomotor movements, the trajectories of their limbs, and the forces they produce. Based on thousands of observations of hundreds of children, researchers in the 1930's concluded that the normative development of locomotion was stage-like, identifying, for example, nearly two dozen stages of prone progression, from "passive kneeling" (Stage 1) to crawling on hands and knees (Stage 19) and beyond (Gesell, 1933, 1946; Gesell & Thompson, 1938), and multiple stages in the development of upright locomotion, from newborns' stepping movements to independent walking (McGraw, 1932, 1935, 1945; Shirley, 1931).

The second part of the traditional answer to the question of how infants move concerns how infants acquire the strength and balance to hoist themselves up and around. The original answer was informed and constrained by researchers' reliance on data from infants' locomotion over uniform paths and by the assumption that locomotion unfolds in stages. Gesell, McGraw, and the other early pioneers took the presumed invariance of the locomotor stages as evidence that neural maturation was the driving force of development and that each stage reflected the underlying status of infants' neuromuscular system (Gesell & Ames, 1940; Gesell & Thompson, 1934; Halverson, 1931; Shirley, 1931; McGraw, 1945). On this account, maturation of neural structures and circuitry allows infants intentional control of their limb movements (Forssberg, 1985; McGraw, 1935, 1945), and affects strength and balance by increasing the efficiency and speed with which perceptual information and motor signals are integrated and processed (Zelazo, 1998; Zelazo, Weiss, & Leonard, 1989).

Many modern researchers have shared the traditional emphasis on describing developmental changes in infants' crawling and walking movements over flat, uniform ground, and in understanding the origins of these locomotor patterns. Rather than reifying developmental changes into stages, modern researchers describe the shape of the developmental trajectories in crawling and walking and the relations between various measures of locomotor proficiency (e.g., Adolph, Vereijken, & Denny, 1998; Adolph, Vereijken, & Shrout, 2003; Bril & Breniere, 1989, 1992). Rather than relying solely on changes in the brain to explain the developmental origins of locomotion, modern researchers also stress the role of peripheral, biomechanical factors, and the role of experience (for review, see Adolph & Berger, 2006).

New View

Ironically, the abundance of laboratory data collected over the past 100 years with infants crawling and walking at a steady pace over short, straight paths on flat ground cannot speak to the variety and novelty of infants' everyday experiences with balance and locomotion. Outside the laboratory, infants travel along circuitous paths for large distances over variable ground surfaces with different walking speeds (Adolph, 2002; Garciaguirre & Adolph, 2006). In the course of a normal day, infants travel over nearly a dozen different indoor and outdoor surfaces varying in friction, rigidity, and texture. They visit nearly every room in their homes and they engage in balance and locomotion in the context of varied activities. Locomotor experience is distributed in bouts of activity, occasionally over large distances, but most frequently involving only a few steps. Movement is interspersed with periods of quiet stance, when infants stop to rest, play with objects, or interact with caregivers. Sometimes bouts end abruptly when infants fall, and sometimes bouts end more smoothly when infants' attention is captured by new features of the environment.

Thus, there is a very different interpretation of the question about how infants move. This new view is concerned with the adaptiveness of infants' locomotor decisions: How do infants select the appropriate locomotor method for getting from one place to another, modify their ongoing movements appropriately, and discover alternative methods of locomotion to cope with new situations? At the same time that infants acquire new locomotor skills, their bodies and environments are undergoing dramatic developmental change. Infants' body growth is episodic: They can wake up to find themselves 0.5 to 1.65 cm taller (Lampl, Veldhuis, & Johnson, 1992). Their bodies become less top-heavy and more cylindrical. With their hands freed from supporting functions, walking infants can vary the location of their center of mass just by picking up a toy. More mature body dimensions and proficient locomotor skills provide infants with increased access to the environment and spur caregivers to allow them greater latitude to encounter novel features of the environment on their own (e.g., removing the gates barring infants from stairs). In short, the new interpretation for the question of how infants move concerns how infants cope with a variable body in a changeable world.

Part of the new answer lies in new methodological approaches to the study of locomotor development. Rather than testing infants on flat, uniform ground, researchers have designed new paradigms that challenge infants with variable features of the environment (e.g., E. J. Gibson et al., 1987; E. J. Gibson & Walk, 1960; Joh & Adolph, 2006; Schmuckler, 1996). For example, researchers have varied the slant, friction, and rigidity of the ground surface, created gaps in the path, terminated the path in a cliff, blocked the path with overhead or underfoot barriers, varied the height of stair risers and pedestals, varied the width of bridges spanning a precipice, and varied the substance and extent of handrails used for manual support (for reviews, see Adolph, 1997, 2002, 2005; Adolph & Berger, 2005, 2006; Adolph, Eppler, & Gibson, 1993b). The focus is on the strategies infants use to cope with the various obstacles and the adaptiveness of their locomotor decisions. Measures of movement kinematics and forces are used in the service of addressing how well suited infants' movements are to the current environmental constraints.

Chapter Overview

This chapter describes examples of the new view of locomotor development. We describe the development of infants' ability to detect and exploit possibilities for locomotion, using slopes, gaps, bridges, and stairs as case studies. Most infants have never navigated slopes, gaps, and bridges on their own (caregivers prevent infants from approaching a precipice), so that these tasks provide a way to observe infants' ability to cope with a novel, potentially risky situation. We focus on how infants gather perceptual information and how they use that information to gauge the possibility or impossibility of crawling or walking. We also discuss how infants learn to solve complex locomotor problems that require cognitive skills for planning and constructing movement strategies. If infants perceive crawling or walking to be possible, they must decide whether to modify their ongoing movements. If crawling or walking is deemed impossible, infants must devise an alternative solution and implement it.

Perceiving Affordances for Balance and Locomotion

Distinguishing Possible from Impossible Actions

The ability to detect affordances lies at the heart of adaptive locomotion. Affordances are possibilities for motor action. Actions are possible only when there is a fit between infants' physical capabilities and the behaviorally relevant features of the environment (J. J. Gibson, 1979; Warren, 1984). For example, walking is possible only when infants have sufficient strength, postural control, and endurance relative to the distance they have to walk, obstacles along the way, and the slant, rigidity, and texture of the ground surface. In fact, the body and environment are so intimately connected for supporting motor actions that changes in a single factor on either side of the affordance relationship alter the probability of successful performance. On the body side of the affordance relationship, for instance, as the weight of a load increases, walking becomes impossible. As balance control increases with development, infants can navigate steeper slopes. Reciprocally, on the environment side of the affordance relationship, as the degree of slant increases, walking becomes impossible. With increase in surface traction, infants can walk over steeper slopes. The ability to detect affordances means that infants can take into account both the constraints of their bodies and of the environment when carrying out their movements.

Investigation into infants' perception of affordances has required the design of new laboratory paradigms. The tasks must be novel to control for infants' previous experience and to ensure that infants' behaviors reflect their spontaneous perception of the possibilities afforded by the experimental apparatus. For example, most infants have never descended a steep slope or playground slide on their own. Thus, in a series of studies, infants encountered slopes in the middle of an otherwise flat path (e.g., Adolph, 1995, 1997; Adolph & Avolio, 2000; Adolph, Eppler, & Gibson, 1993a; Mondschein, Adolph, & Tamis-LeMonda, 2000). As shown in Figure 1, flat starting and landing platforms flanked an adjustable slope. By pressing a remote switch or cranking a jack, the slope could be adjusted to any degree of slant between 0° (flat) and 90° (sheer drop-off). Parents stood at the bottom of the slope encouraging their infants to descend. An experimenter followed alongside infants to ensure their safety. The degree of slant varied from trial to trial, so that some slopes were perfectly safe, some were impossibly risky, and a narrow band of slopes had a shifting probability of success. The primary outcome measures were whether and how infants decided to descend safe and risky slopes to reach the goal at the bottom.

After 10 weeks or so of crawling or walking experience, infants geared their locomotor decisions to the possibilities for action. On trials when slopes were within their abilities, infants crawled or walked to the bottom of the walkway. However, when slopes were beyond their abilities, infants refused to crawl or walk down. After 20 weeks of crawling or walking experience, infants' perception of affordances matched the actual possibilities for action within a few degrees of accuracy. That is, infants' rate of attempts closely matched the conditional probability of success. Information-gathering behaviors became more efficient as the accuracy of infants' motor decisions improved (Adolph, 1995, 1997). Infants looked down the slope as they approached it over the starting platform. They stopped at the edge and generated haptic information from touching. Crawlers put both hands on the slopes and rocked back and forth over their wrists. Walkers stood at the brink of the slopes and rocked back and forth around their ankles. Latency, looking, and touching increased on risky slopes.

Figure 1

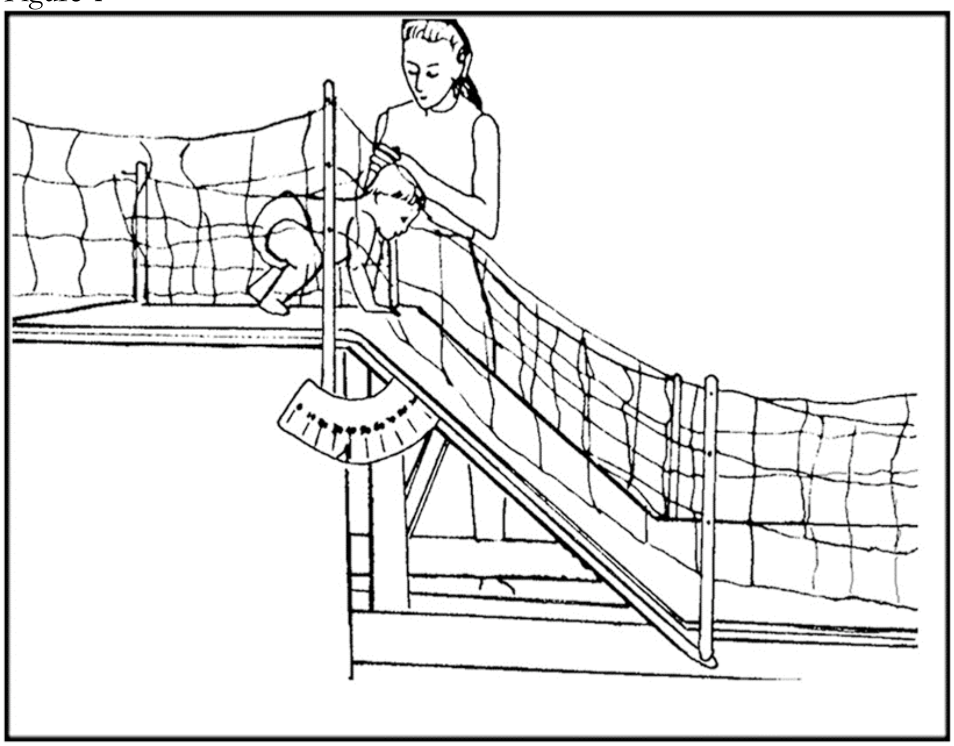

Figure 1. Mechanized walkway with adjustable slope (0° to 90°). Slant was varied by operating a drive screw with a hydraulic lift. Infants began each trial on the starting platform and traversed the sloping middle section while an experimenter (shown) followed alongside for safety. Parents (not shown) waited at the far end of the walkway. Reprinted from the *Monographs of the Society for Research in Child Development, 62*(3, Serial No. 251), by K. E. Adolph, "Learning in the development of infant locomotion," 1997, with permission from Blackwell Publishers.

Infants' ability to detect affordances is especially impressive because the possibilities for action change from week to week. Affordances were related to naturally occurring changes in infants' body dimensions, level of locomotor skill on flat ground, and duration of everyday locomotor experience: More maturely proportioned, proficient, and experienced crawlers and walkers, could crawl and walk down steeper slopes. Thus, detecting affordances required infants to relate changes in the degree of slant on each trial to their current bodily propensities. A risky slope one week might be perfectly safe the next week after crawling or walking skill improved. A safe slope for crawling might be risky for walking.

In fact, experienced walking infants were so sensitive to both terms of the affordance relationship that they could simultaneously update their assessment of affordances based on experimental manipulation of their body dimensions and walking proficiency, and to variations in the slope of the ground surface. Fourteen-month-old walking infants were outfitted in a vest with shoulder-packs that could be filled with different loads (Adolph & Avolio, 2000). The weight of the shoulder-packs changed at the start of each trial. On some trials, the packs were filled with lead-weights (25% of infants' body weight). On other trials, the shoulder-packs were filled with feather-weight Polyfil to serve as a control for the heavy condition. The lead-weight packs experimentally changed infants' body proportions to make them more top-heavy and immaturely proportioned (Figure 2). As a consequence, the heavy loads also decreased infants' walking proficiency on flat ground and slopes. Infants recalibrated their perception of affordances from trial to trial: They treated the same degree of slope differently depending on whether they were wearing feather- or lead-weight packs. Infants were more likely to attempt to descend a given degree of slant wearing the feather-weight packs than when they were wearing the heavy packs.

Figure 2

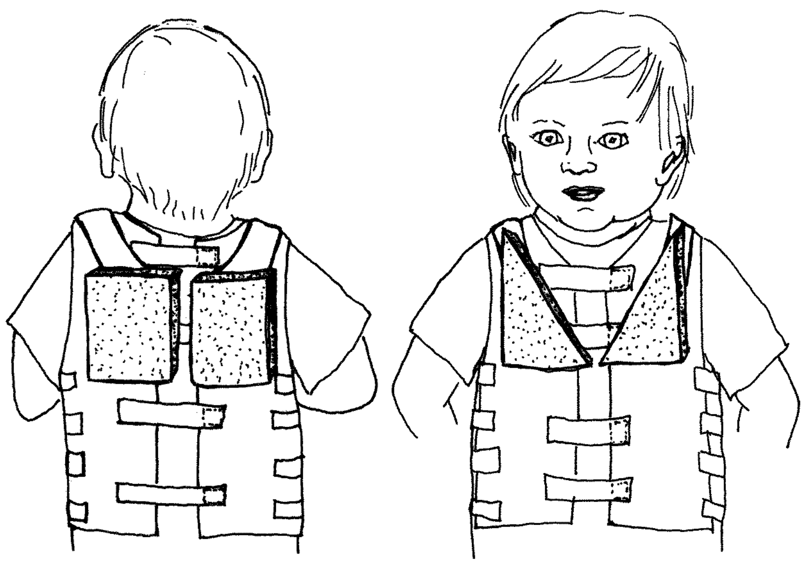

Figure 2. Velcro vest with removable shoulder packs. Reprinted from J. Lockman, J. Reiser, & C. A. Nelson (Eds.), Action as an organizer of perception and cognition during learning and development: Symposium on Child Development (Vol. 33), by K. E. Adolph, "Learning to learn in the development of action," pp. 91-122, 2005, with permission from Lawrence Erlbaum Associates.

Experienced infants can detect affordances for stance as well as for locomotion. In stance, the base of support is stationary, but typically the rest of the body is moving—head, arms, and torso move while in sitting and standing positions. We turn to look at something, lift our arms to reach for something, nod, cough, stretch, and bend. Each movement changes the location of infants' center of mass and creates new destabilizing torque. If infants reach or lean too far in any direction, they will lose balance and fall. To test infants' perception of affordances for maintaining balance in stance, 9.5-month-olds were perched in a sitting position at the edge of an adjustable gap (Adolph, 2000). The gaps apparatus was composed of a fixed starting platform and a movable landing platform. The landing platform slid back and forth along a calibrated track to create gaps 0 to 90 cm wide between the two platforms. A lure offered at infants' chest height from the landing platform encouraged them to lean forward and stretch an arm out to reach (Figure 3). Caregivers also offered encouragement from the far side of the landing platform. An experimenter stood nearby infants to rescue them if they fell into the precipice.

Figure 3

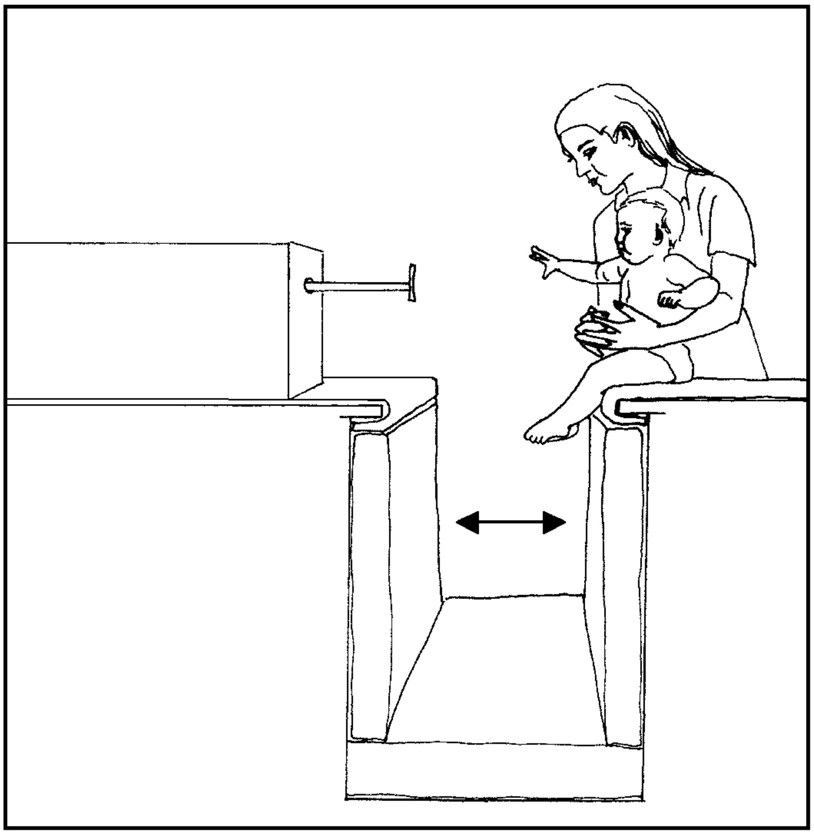

Figure 3. Illustration of the adjustable gaps walkway for testing sitting infants' perception of affordances. Gap width varied from 0 to 90 cm by pulling the landing platform along a calibrated track. A sitting infant leaning forward over a gap in the surface of support. An experimenter (shown) walked alongside for safety. Parents (not shown) waited at the far end of the walkway. Reprinted from *Psychological Science*, by K. E. Adolph, "Specificity of learning: Why infants fall over a veritable cliff," pp. 290-295, 2000, with permission from Blackwell Publishers.

Although the gap situation was new, infants were experienced sitters (on average, 15 weeks of experience with independent sitting) and they could detect precisely how far forward they could reach and lean without falling into the gap. On safe gap widths within their ability, infants leaned forward to retrieve the lure. But, on risky gap widths beyond their ability, infants refused to reach. Infants occasionally extended and retracted their arm without touching the lure, as if to explore the limits of the reaching space.

Occasionally, affordances for locomotion are expanded when features of the environment (a handrail or ladder) or extensions of the body (a walking stick or crutch) are used as a means, or tool, for mobility. Tools can make otherwise impossible actions possible. Handrails and walking sticks, for example, can be used to augment balance in a treacherous situation. Ladders and climbing/sliding poles can make distant targets accessible. Typically, researchers consider infant tool use only in terms of hand-held implements such as rakes, spoons, and hammers (e.g., Achard & von Hofsten, 2002; Chen & Siegler, 2000; Lockman, 2000; McCarty, Clifton, & Collard, 2001; McCarty & Keen, 2005). However, recent work shows that experienced walking infants exhibit whole body tool use to expand affordances for locomotion.

By the time infants are 16 months old, their perception of affordances for locomotion is so sophisticated that they can use a handrail as a means for augmenting their balance while crossing narrow bridges (Berger & Adolph, 2003). Infants were encouraged to walk over wide and narrow bridges (12 cm to 72 cm) spanning a deep precipice between two flat platforms (Figure 4). On half of the trials, a sturdy, wooden handrail ran the length of the bridge. On the other half of the trials, the handrail was absent. Parents stood at the far side of the precipice, offering infants toys as a lure, and an experimenter walked alongside infants for safety. Overall, infants were highly accurate in judging their ability to walk over bridges (94% of trials were successful). Regardless of whether the handrail was available, infants crossed the wide bridges (48 cm to 72 cm) and avoided the narrowest bridge (12 cm). On intermediate bridges (18-36 cm), infants walked more often when the handrail was available than when it was absent. Use of the handrail varied with bridge width. On wide bridges, the infants ignored the handrail; they ran straight across without touching the rail or they briefly tapped it with one hand in passing. On the 36-cm bridge, they used the handrail by facing forward and sliding one hand along the rail. On the 18- and 24-cm bridges, they turned sideways to face the rail and clutched on with both hands.

Figure 4.

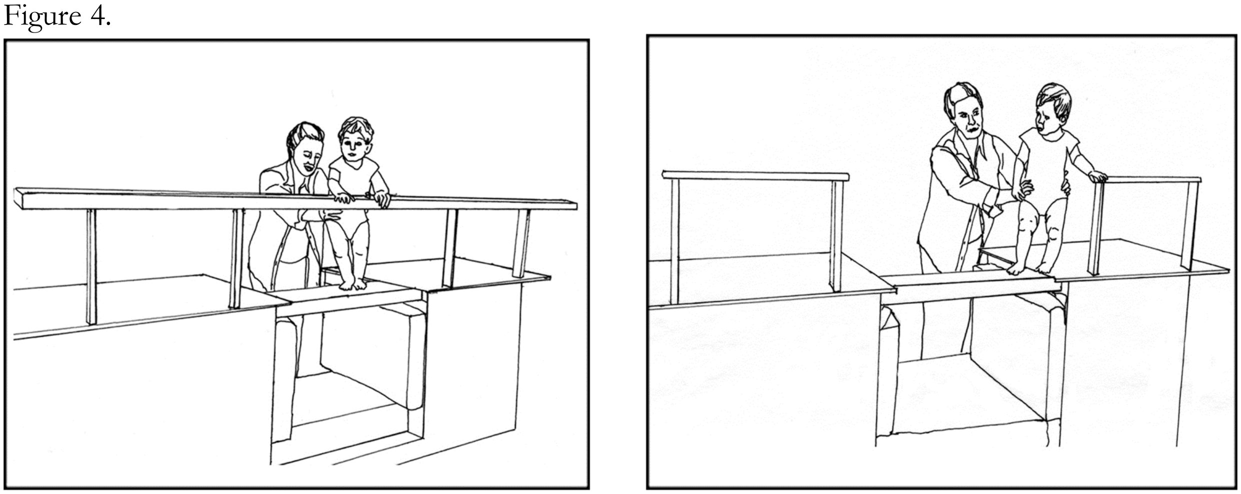

Figure 4. Walkway with adjustable bridge widths and removable wooden handrail. (a) On handrail trials, a handrail spanned the length of the bridge and rested on permanent support posts. (b) On non-handrail trials, the permanent support posts remained on the starting and finishing platforms. The drop-off beneath the bridge was lined with foam padding. Infants began each trial on the starting platform. Parents (not shown) stood at the far end of the finishing platform offering encouragement. An experimenter (shown) followed alongside infants to ensure their safety. An assistant (not shown) adjusted the bridge widths by fitting them into a grooved slot, and switched the handrails by placing the on the support posts. Reprinted from *Developmental Psychology*, *39*(3), by S. E. Berger & K. E. Adolph, "Infants use handrails as tools in a locomotor task," pp. 594-605, 2003, with permission from the American Psychological Association.

A follow-up study showed that infants took the material substance of the handrail into account when gauging its use as a tool for augmenting balance (Berger, Adolph, & Lobo, 2005). Handrails were presented on every trial, but on some of the trials, the handrail was sturdy wood and on other trials the handrail was wobbly foam or rubber (Figure 5). On intermediate bridges, infants walked more often when the handrail was sturdy and could support their weight than when the handrails were wobbly. These findings suggest that infants perceived the wooden handrail as a structure in the environment, separate from themselves and from the bridges, that could afford bridge crossing by augmenting balance.

Figure 5.

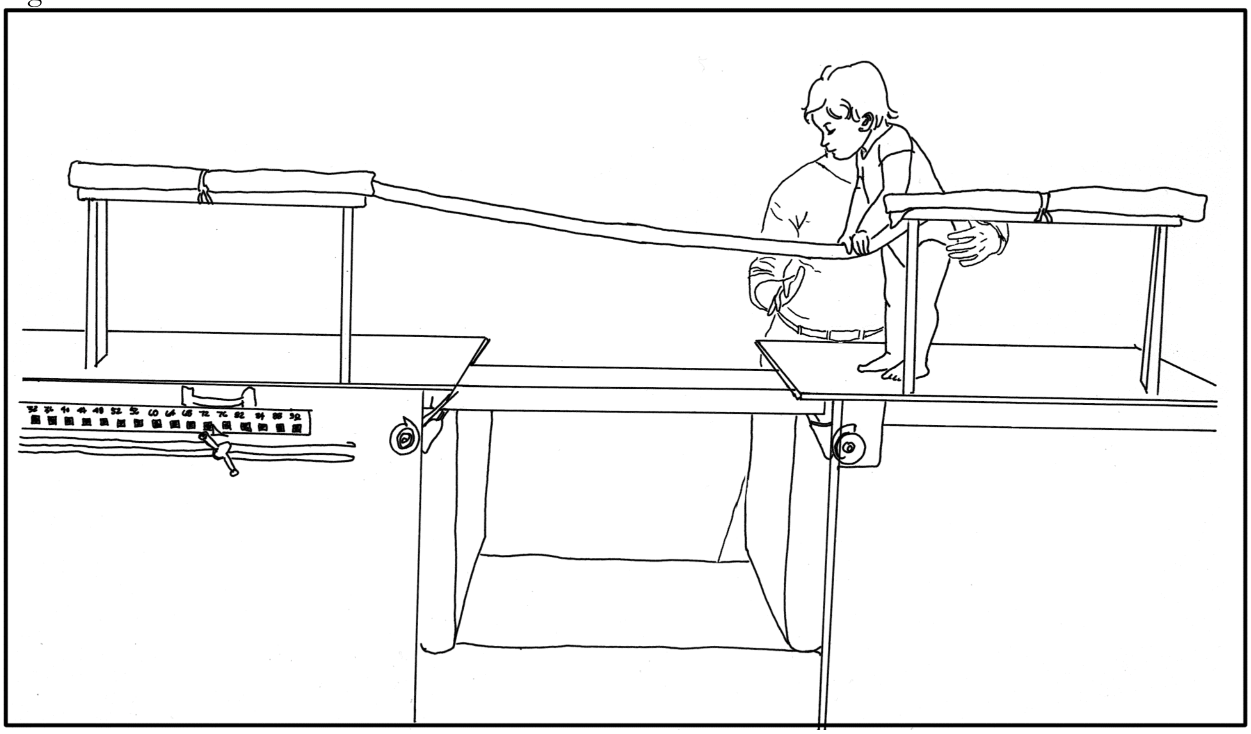

Figure 5. Walkway with adjustable bridge widths and removable wobbly (foam or latex) handrail (shown with 20 cm bridge). Parents (not shown) stood at the far end of the finishing platform offering encouragement. An experimenter (shown) followed alongside infants to ensure their safety. Reprinted from *Child Development, 76*, by S. E. Berger, K. E. Adolph, and S. A. Lobo, "Out of the toolbox: Toddlers differentiate wobbly and wooden handrails," pp. 1294-1307, 2005, with permission from Blackwell Publishers.

Modifying Ongoing Movements

In a busy, natural environment—or while crossing slopes, bridges, and other situations designed for laboratory experiments—detecting affordances for locomotion requires more than deciding whether to crawl and walk. In addition, infants must modify ongoing crawling and walking movements to suit the current constraints on balance and locomotion. Task constraints, such as the degree of slant or the bridge width, can change from trial to trial. The situation might demand slowing down or speeding up, alterations in step length, turning the body, stooping over, lifting the legs, and so on. How is this accomplished? Experienced crawling and walking infants can plan modifications prospectively, before stepping over the brink of a slope or onto a bridge, concurrently, by monitoring and updating locomotion from step to step, and reactively, in response to a loss of balance.

Prospectivity has practical advantages. Planning gait modifications prior to encountering an obstacle allows infants to prevent themselves from falling, rather than having to recover as they begin to fall. For example, experienced crawling and walking infants take smaller, slower steps to cross steep slopes and narrow bridges (Adolph, 1997; Berger & Adolph, 2003; Berger et al., 2005). The evidence that gait modifications are prospective rather than reactive is that infants begin to curtail their step length and velocity on the starting platform, and turn their bodies to grasp the handrail, in anticipation of stepping onto the obstacle (Berger et al., 2005; Gill-Alvarez & Adolph, 2005). Visual information for the upcoming threat to balance is sufficient to prompt the behavioral changes. Experienced crawling and walking infants do not have to feel themselves lose balance in order to modify ongoing movements.

Prospective gait modifications are exquisitely attuned to small changes in slant and bridge width. Across experiments, on shallow slopes well within their abilities, infants crawled or walked normally with large, fast steps. But, as slant increased and slopes challenged the limits of their abilities, infants modified their gait by taking smaller steps and more time to reach the goal. Walkers maintained a more stiffly upright posture and crawlers braced themselves by stiffly extending their arms. These gait modifications and postural adjustments served to brake infants' forward momentum from step to step, and thus allowed them to crawl and walk safely down a steeper range of slopes.

Narrow bridges posed a different problem: Rather than fighting gravitational forces as they moved along the bridge, infants had to fit their bodies into a limited space. The narrowest bridges were narrower than the width of infants' shoulders. On wide bridges infants faced forward and walked as usual, but on narrow bridges they modified their gait and posture. Some infants took more than 25 baby steps and longer than 30 seconds to travel 74 cm over the narrower bridges (Berger et al., 2005). In addition, infants turned their bodies sideways. Rather than using an alternating gait, where each foot traveled a farther distance than the last, they inched along with the trailing leg never passing the leading leg.

Even after infants have committed to crawling or walking over an obstacle, they continue to monitor and update their motor plans. Gait modifications can occur concurrently while taking advantage of the affordance. For example, on intermediate slopes, crawling infants sometimes lowered their chests from a high hands-and-knees position to a lower position with legs splayed wide, momentarily resting their chests on the surface to regain balance (Adolph, 1997). While walking over bridges, infants sometimes began with their bodies facing forward. Then, mid-bridge, they turned their bodies sideways so that they could grab the rail with two hands instead of one, and so that their bodies would fit better on the bridge (Berger & Adolph, 2003). On challenging bridges, infants inched along and then occasionally took a giant step when they neared the end of the bridge as if to facilitate a quicker exit to the landing platform. Updating in the midst of exploiting an affordance generally involved a switch from a less efficient, more precarious gait pattern to a more efficient, more stable strategy. Changes implemented on one trial frequently carried over to the next.

Reactive adjustments are less efficient (infants fall more frequently) than prospective and concurrent gait modifications. However, in situations where access to information about an upcoming perturbation is lacking, infants have no way to prepare for the obstacle, and reactive adjustments are the only option. For example, with the sudden addition of a load, the body can only react to the new distribution of forces. To assess reactive gait modifications and postural adjustments to load carriage, 14-month-old infants were challenged with the sudden addition of symmetrical and asymmetrical loads (15% of body weight) as they walked over flat ground (Garciaguirre, Adolph, & Shrout, in press). The loads were distributed on the front, side, and back of infants' bodies and symmetrically across infants' chests and backs. The distribution of the load varied from trial to trial, so that infants could only determine the location of the load as they felt their bodies begin to tip.

Depending on the load condition, infants displayed 2 to 5 times as many trials with gait disruptions compared with a feather-weight baseline condition. Infants coped with the lead-weight loads by decreasing their step length and walking speed and spending a greater proportion of the gait cycle with both feet on the ground and a smaller proportion of the gait cycle with one foot in the air. The gait modifications were reactive—infants felt themselves pulled off balance and then changed their walking patterns. Although adults show reactive modifications in posture by leaning in the opposite direction of the weights (think of leaning to the left while carrying a heavy suitcase in your right hand, or leaning forward while wearing a heavy backpack), infants reacted by leaning with the loads: They leaned forward while carrying the load in the front, leaned to the right while carrying the load on their right side, and so on. Apparently, infants' reactive gait modifications merely accommodate to the loads, whereas adults' reactive modifications compensate for the loads.

New Solutions

To infants, the everyday environment is sometimes like a playground, pregnant with possibilities for playful forms of mobility, and sometimes like an obstacle course, rife with challenges. Crawling and walking are the most studied forms of infant locomotion, and sitting and standing are the most studied forms of stance, but these forms are not infants' sole means of mobility and balance. In situations that offer or demand alternative forms of locomotion, infants jettison their typical crawling and walking postures and search for new solutions. Infants' use of sliding, scooting, backing, and countless other alternative methods of locomotion not only inform on their perception of affordances, but, in addition, provide insights into the acquisition of new behavioral forms.

Multiple Solutions

Generally, infants find multiple and variable solutions for navigating challenging terrain, rather than a single, fixed approach. For example, successful navigation during descent, such as on a slope, staircase, or drop-off, requires strength and balance to fight gravity as the body is simultaneously lowered and moved forward. Both crawling and walking are difficult during descent because infants' body weight must be supported on a bent limb (an arm in crawling and a leg in walking), requiring more muscle strength than on a fully extended limb during ascent or on flat ground. Thus, on slopes and stairs, walking infants sometimes augmented their balance by holding an available handrail or grabbing onto the experimenter for extra support (Adolph, 1997; Berger, 2004). On steep slopes and stairs, infants abandoned their typical crawling and walking methods in favor of alternative strategies that lowered their center of mass and provided more balance control (Figure 6). On some trials, infants slid down on their bellies, Superman-style, with arms extended straight in front on their heads and legs extended straight behind. On other trials, infants slid down on their bottoms in a sitting position. On still other trials, infants slid down backward, facing away from the landing platform (Adolph, 1997). Similarly, walking infants descended a steep staircase in a sitting position, scooting down from riser to riser, and in a backing position, crawling or sliding down with their heads pointing away from the floor (Berger, 2004).

Experienced walking infants frequently revert to crawling when balance is threatened. Walkers switch from upright to crawling to descend steep slopes on their hands and knees (Adolph, 1995, 1997; Adolph et al., 1993a), to cross a squishy waterbed (E. J. Gibson et al., 1987), and to cross narrow bridges (Berger & Adolph, 2003; Berger et al., 2005). Similarly, experienced hands-and-knees crawlers frequently revert to belly crawling for descending steep slopes (Adolph, 1997). The earlier developing form of locomotion appears in infants' repertoires as an alternative strategy before they exhibit new strategies such as sliding down slopes in sitting and backing positions (Adolph, 1997).

Figure 6.

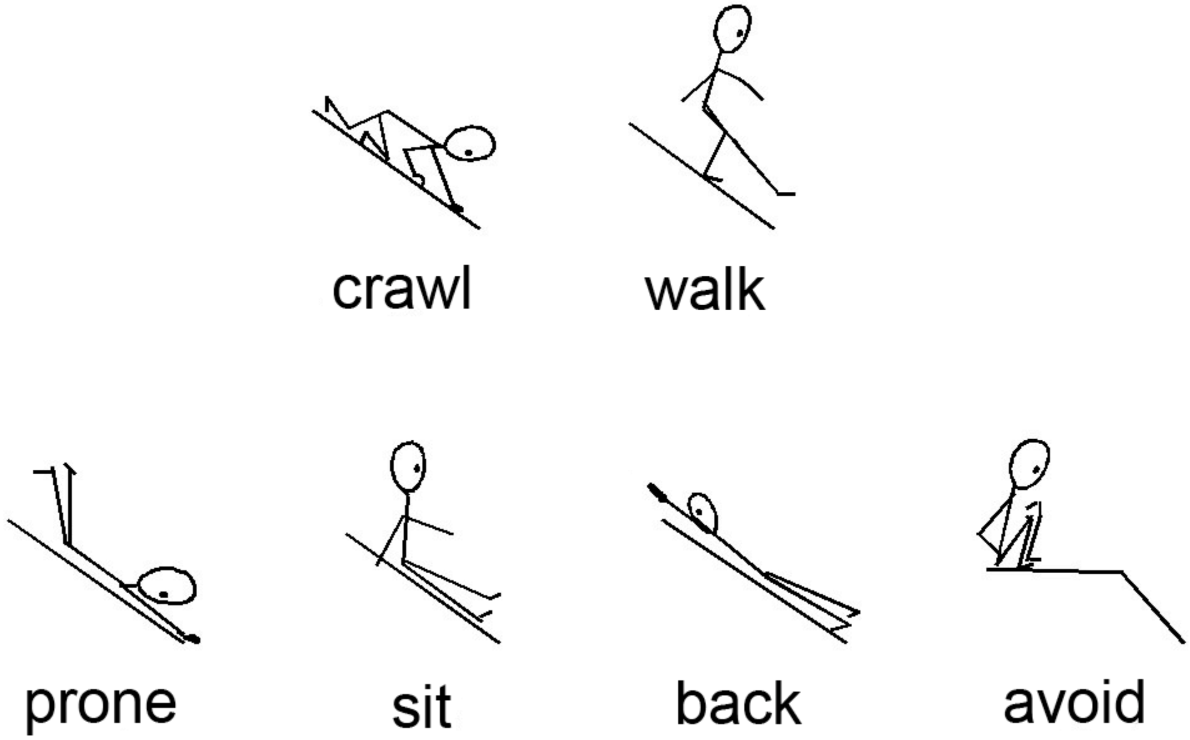

Figure 6. Illustration of infants' typical methods and alternative strategies for descending slopes. Reprinted from the *Monographs of the Society for Research in Child Development, 62*(3, Serial No. 251), by K. E. Adolph, "Learning in the development of infant locomotion," 1997, with permission from Blackwell Publishers.

Researchers often find themselves outwitted by infants' ingenious solutions to experimental challenges. Indeed, infants may inadvertently benefit from their ignorance about the conventional uses of an apparatus, so that they perceive affordances where adult researchers see none. The standard visual cliff apparatus, for example, is composed of a large, rectangular glass table bisected by a narrow starting board to form two square sides (E. J. Gibson & Walk, 1960). On the "shallow" side, a textured surface abutting the glass provides visual information for solid ground. On the "deep" side, the textured surface lies on the floor far below the safety glass, providing visual information for an abrupt drop-off. A raised wooden wall along the outer edges of the apparatus prevents infants from falling to the floor. Infants are placed on the starting board near one of the long sides (due to the size of the apparatus, the experimenter cannot reach the middle of the starting board), and caregivers stand at the far diagonal corner, first on the shallow end and then on the deep end. On the shallow side, experienced crawling infants go straight to their caregivers in a beeline to the diagonal corner. On the deep side, they sometimes avoid crossing by remaining on the starting board. However, infants sometimes use an ingenious detour strategy: They cruise along the wooden walls, so that their hands are always in contact with a solid surface, and their faces are pointing out rather than looking down at the floor beneath the safety glass (Campos, Hiatt, Ramsay, Henderson, & Svejda, 1978; Witherington, Campos, Anderson, Lejeune, & Seah, 2005). In addition, infants "backed" over the safety glass (turned around and crawled backwards to their caregivers), using the same sort of strategy that would be effective if the drop-off were real rather than illusory.

In the "wobbly handrails" experiment, the wobbly rail conditions were intended to be equivalent to the no-handrail conditions in the previous set of studies; the foam and rubber handrails were designed to give way when the infants leaned their weight on them—as indeed they did (Berger et al., 2005). Nonetheless, infants discovered new solutions for crossing narrow bridges with only a wobbly handrail for support (Figure 7). Most frequently observed was a "hunchback" strategy, where infants walked sideways, stooped over, pressing down on the wobbly handrail. Infants also used a "snowshoe" strategy, where infants walked forward while resting their entire arm on the handrail to prevent it from dipping too deeply, just as snowshoes prevent walkers from plunging through the snow; a "mountain-climbing" strategy, where infants leaned backward while walking forward and pulled up on the handrail like a rope, dragging themselves along hand-over-hand; a "windsurfing" strategy, where infants walked sideways along the bridge, leaned backward and pulled up on the handrail as high as it would go with both hands; and a "drunken" strategy, where infants faced forward and leaned sideways against the railing, sliding their torsos along the handrail. Infants' alternative strategies were hilarious to observe, but also critical functionally. Infants who adopted one of the alternative handrail strategies were more likely to cross narrow bridges successfully than infants who did not.

Figure 7.

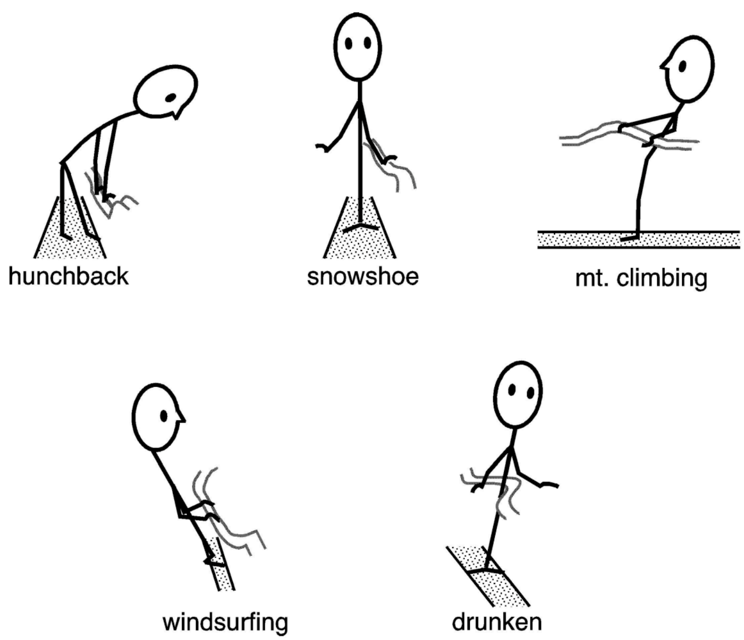

Figure 7. Illustration of infants' alternative strategies for using the "wobbly" handrails. Reprinted from *Child Development*, *76*, by S. E. Berger, K. E. Adolph, and S. A. Lobo, "Out of the toolbox: Toddlers differentiate wobbly and wooden handrails," pp. 1294-1307, 2005, with permission from Blackwell Publishers.

Variety of means does not merely reflect differences between infants. Although any single alternative would suffice for navigating an obstacle, many infants use multiple strategies (Siegler, Adolph, & Lemaire, 1996). Individual infants use multiple alternative strategies on different trials within the same test session, and multiple means on the same trial. For example, across ages, most infants treated the same degree of slope differently within the same experimental session by using different alternative sliding strategies on different trials for the same increment (Adolph, 1997). While descending stairs, almost all infants (95%) used more than one descent strategy on stairs within the test session and almost all (90%) used more than one descent strategy within the same trial. For example, infants started down the stairs in a sitting position, but partway down switched to backing (Berger, 2004). While using a wobbly handrail to cross narrow bridges, infants often used several of the alternative strategies for crossing (e.g., started with "hunchback" and switched to "snowshoe") in the same trial (Berger et al., 2005).

Situations where infants cannot find a viable alternative tend to be most frustrating, and happily were most rare in laboratory studies. On trials where infants avoided traversal, they did not simply freeze at the brink of the obstacle. However, sometimes their search for alternatives was interrupted by bouts of displacement activities, as if they needed a break from the problem, and sometimes they found a way to escape from the situation entirely. For example, when infants were encouraged to descend a short, very steep, 36° slope and a long, shallow 10° slope, each slanting from a small, 55-cm high platform (Figure 8), infants occasionally avoided the whole situation by scooting down from the backside of the platform rather than descending to their parents at the bottom (Eppler, Adolph, & Weiner, 1996). Similarly, infants sometimes scooted off the backside of the starting platform (54-cm high) rather than descend a small staircase (Berger, 2004) and detoured off the side of the starting platform rather than cross a large, deformable foam pit (Joh & Adolph, 2006). In situations that did not allow a detour (the starting platform was too high, or escape was blocked by a wall), infants coped with the frustration of facing an insurmountable obstacle with displacement behaviors. When facing steep slopes or a rippling waterbed, frustrated infants turned their attention to the overhead ceiling lights, a crumb on the carpet, or their own belly buttons and diapers (Adolph, 1997; E. J. Gibson et al., 1987). Nine-month-old sitting infants' response to impossibly wide gaps was a most emphatic rejection: They pivoted away from the gap as if to shut out the sight of their caregivers offering the attractive lure (Adolph, 2000). They sat facing the back wall with their arms crossed until trials thankfully came to an end.

Figure 8.

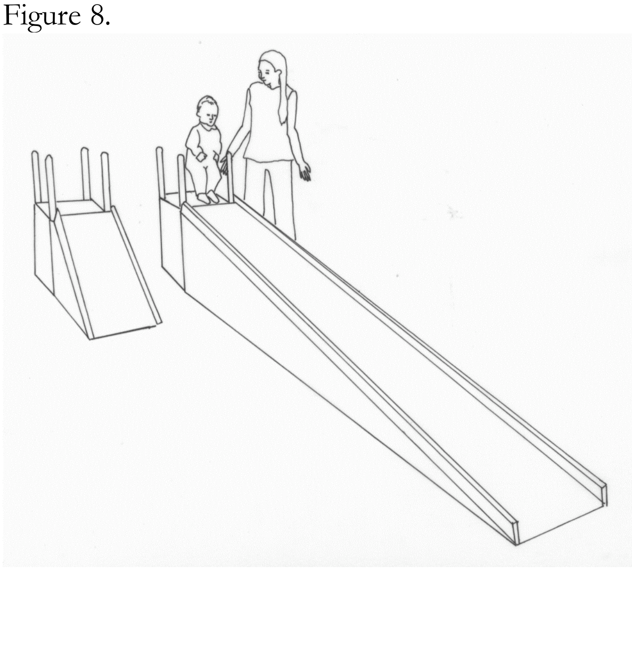

Figure 8. Short, steep, 36° slope and long, shallow 10° slope. Infants started each trial on a platform and an experimenter (shown) walked alongside for safety. Parents (not shown) called to their infants from the bottom of each slope. Reprinted from *Infant Behavior and Development, 19*, by M. A. Eppler, K. E. Adolph, & T. Weiner, "The developmental relationship between infants' exploration and action on slanted surfaces," pp. 259-164, 1996, with permission from Elsevier.

The variety of alternative strategies that infants exhibit for using handrails, descending slopes, and crossing the visual cliff and detour behaviors that remove infants from a frustrating task provide evidence that infants detect an array of affordances—rather than a single solution—for balance and locomotion. Thus, as infants approach an obstacle in their typical crawling or walking posture, they decide whether to continue with their typical method of locomotion, whether to modify their typical method, or whether an alternative strategy is required (Adolph, Eppler, Marin, Weise, & Clearfield, 2000). In the latter case, they must figure out an appropriate alternative—by drawing on a pre-existing strategy in their repertoire, constructing a new strategy on the fly, or by trying various strategies until finding one that works.

Explicit Instruction

How do infants add new skills to their repertoire of locomotor strategies? One possibility is explicit instruction. Parents might teach infants to execute a new form of locomotion by physically moving the appropriate parts of infants' bodies into the appropriate configurations, modeling the target behavior for infants, and using words and gestures to explain to infants what to do. One situation where infants learn new strategies by explicit instruction is descending stairs.

Infants encounter stairs in their own homes, in the homes of friends and relatives, and outdoors in parks and playgrounds. In a study of 732 families investigating the circumstances surrounding how and when infants learn to navigate stairs (Berger, Theuring, & Adolph, in press), many parents (58%) reported that they explicitly attempted to teach their infants safe strategies for descending stairs. Parents' most frequent teaching method was hands-on training. They turned infants' bodies at the top landing and moved their arms and legs onto each riser to show them how to get down. Less frequently, parents modeled stair descent by getting down on all fours on the stairs and crawling backward. Parents also gave verbal instructions, such as "turn around and back down" and encouragement such as "good job." Most parents reported using several of these teaching strategies in combination.

Because of the risks associated with descending stairs, most parents preferred that their infants descend in a backing position on their hands and knees because they deemed it safer than attempting to walk, scooting down sitting, and crawling/sliding head-first. Parents' preference for backing may account for why so many infants were taught to descend stairs, rather than left to discover a strategy on their own. Backing is the most cognitively demanding descent strategy because it requires that infants coordinate several steps into the proper sequence: First, infants must switch from upright to a prone position, then they must pivot their bodies 180° so that they are facing away from the bottom landing, and finally, infants must move their bodies backwards. The initial detour may be especially problematic. Turning away from their destination is difficult for young infants because they tend to be visually and motorically "captured" by a goal (Diamond, 1990b; Lockman, 1984; Lockman & Adams, 2001; McGraw, 1935). Although moving backward is not difficult motorically, it is difficult perceptually and cognitively. Infants must give up sight of the goal and deliberately move toward a goal that is only represented, not seen. Thus, it is reasonable that parents determined that their young infants should be helped through the process.

Explicit instruction, however, has limitations. Generally, parents teach their infants the backing strategy on a particular staircase in the home or playground. Learning in the narrow training environment may not transfer when infants encounter a new staircase or a different descent problem where the backing strategy would be useful. Infants who were taught to descend stairs at home using the backing strategy were no more likely to display the backing strategy on laboratory slopes and stairs than infants who had not been taught to back (Adolph, 1995, 1997).

Constructing New Solutions

A second way that infants acquire alternative locomotor strategies into their repertoires is by a process of exploration and construction. As they faced impossibly steep slopes and narrow bridges, experienced infants rarely rested quietly. Instead, they concertedly sought out information, weighed whether a particular posture afforded traversal, and continued to try out different combinations of postures and strategies until a solution was found. They shifted their bodies from one position to another—from standing to sitting to squatting to backing, and so on (Adolph, 1995, 1997; Adolph et al., 1993a). They grasped the handrails and support posts in one body configuration and then tested a second or third configuration. These shifts in position had the quality of a concerted means-ends exploration geared toward a goal.

Sometimes the trials ended with infants back in their original position, no closer to the goal. Sometimes trials ended with infants assuming an appropriate crossing position. Frequently, a position assumed on one trial that was not fully executed was retried on a subsequent trial or trials and executed successfully. For some infants, a new strategy might appear full-blown. For example, one experienced crawler pivoted several times in circles on his belly and then shot himself backward down a steep slope (Adolph, 1997). For other infants, the new strategy might appear piece meal, with a 180° pivot on one trial, and the push backward on a subsequent trial.

Sometimes infants took such delight in a newly acquired alternative strategy that they overgeneralized the need for the strategy and used it on increments that could be easily navigated by crawling and walking. In particular, infants enjoyed sliding down slopes. After their first discovery of a new sliding position, they might attempt to cross shallow slopes or even flat ground by backing or scooting down in a sitting position.

Serendipitous Discovery

Learning new methods for traversing challenging surfaces was not always intentional. A third route for alternative strategies to enter infants' repertoires was serendipity. Like the process of exaptation in evolution, sometimes infants started out using their typical method of locomotion, but unexpectedly found themselves implementing an alternative. In other words, the biomechanics of the situation may have transformed their intended form of locomotion into a useful alternative.

On slopes, backing and sitting entered some infants' repertoires by the serendipitous route (Adolph, 1997; McGraw, 1935). When experienced crawlers attempted to crawl down steep slopes, they kept their arms stiffly extended. With their legs were flexed tightly under their hips, their torsos would be turned sideways due to gravity. Infants would find themselves sliding down sideways. On some trials, infants' bodies would get turned so far around that their feet would be pointing toward the landing platform. Evidence that infants were surprised at this turn of events is that they cried out, "uh oh" and "oh no," crawled back up to the starting platform, and looked down the slope once again in consternation (Adolph, 1997). In time, infants who had several accidental backing trials learned that it was easier to back down a steep slope than to crawl down forward, because it was harder to fight gravity with the heaviest part of their body, their head, going in front. Eventually, infants whose initial backing trials were serendipitous, assumed the backing position before they went over the brink.

Similarly, when crawlers attempted headfirst descent of steep slopes with their knees splayed, rather than glued together, they sometimes ended up with their legs in a straddle-split position. With their stiffly extended arms pushing backward to keep their heads up, infants would accidentally find themselves sliding down in a sitting position. The same infants whose initial sitting trials were serendipitous eventually assumed a sitting position on the starting platform before going over the brink.

The array of strategies for using wobbly handrails may also have been serendipitous (Berger et al., 2005). Infants may have intended to use the wobbly handrails as they would use sturdy ones, but as the wobbly handrails gave way and they found themselves in unusual positions, they would "go with the flow." For example, the "hunchback" strategy may have emerged when infants put their weight on the handrail, as they would with any normal handrail, and it sank to the mid-thigh level. Instead of giving up, as older children and adults might have done, infants simply leaned with the handrail and walked across the bridge sideways, hunched over because that was what the wobbly handrail afforded. Although they may not have begun the trial with the intention of walking hunched over, after finding themselves in that position, they may have accommodated to the circumstances.

Learning by Doing

A final possibility for the acquisition of alternative strategies may be learning by doing. Like diving into a pool to test the water, infants may simply throw themselves into the situation with no intended course of action, and then learn by observing the consequences. Learning by doing may be infants' preferred process of exploration in situations where the consequences of falling are negligible. A prime example is situations involving ascent.

Once infants develop the strength in their arms and legs to hoist their entire weight and keep balance on one limb, a new world of ascending opportunities opens up for them. Now infants can climb up any object onto which they can get a foothold. As any parent who has had to babyproof a home can attest, almost any vertical surface can afford the possibility for climbing. Some humorous examples found in the motor development literature include fences, trees, furniture, cribs, bathtubs and toy boxes (McGraw, 1935; Trettien, 1900; Valsiner & Mackie, 1985). Of course, the most frequently encountered space for climbing is the staircase. Parents report that infants almost always figured out stair ascent on their own (Berger et al., in press).

In the laboratory, where tasks involving ascent can be observed directly, learning by doing seems to be infants' primary means for acquiring new ascent strategies. On slopes, for example, at every age and level of experience, crawlers and walkers flung themselves at the hill on every trial and then observed the consequences (Adolph, 1995, 1997; Adolph et al., 1993a; McGraw, 1935). In fact, infants' attempts appeared to be more geared toward acquiring alternative strategies rather than discriminating affordances for crawling or walking. Attempt rates were always higher for ascent compared with descent, even on impossibly steep slopes. Infants attempted ascent repeatedly on the same trial, happily struggling to get up after sliding back down for the upteenth time.

Sometimes, infants acquired new gait modifications through learning by doing. Crawlers powering up the slope, sliding back down, and powering up again, switched from hands and knees to using their toes to grip the surface. Walkers learned to lean forward into the slope, after pitching backward on repeated attempts. Sometimes, infants acquired alternative strategies from learning by doing. As walkers flung themselves at the slope, they learned to take a running start, then switch to climbing the remainder on hands and feet. Infants in both crawling and walking groups learned methods for gripping the top of the slope with their forearm and swinging a leg over the brink.

Cognition in Motion

On the new view of locomotor development, perception is integral. Traveling over a uniform path at a steady pace encourages infants to execute the same movements over and over. In contrast, navigating through a cluttered environment while adapting to changing goals and varying destinations requires infants to change their movements from step to step. At every point in the development of stance and mobility, infants must use perceptual information to detect the changing constraints on balance and propulsion. To exploit the available affordances, infants must perceive them. And, to perceive the available affordances, infants must turn up the relevant perceptual information by their own spontaneous exploratory movements.

In addition to perception, adaptive mobility involves cognition. Experimental paradigms where infants approach obstacles such as slopes, stairs, bridges, and gaps approximate real-life problems that infants encounter as they wend their way through the maze of household objects, climb over furniture, and scale the equipment at the playground. The problem-solving skills required for coping with such obstacles can involve higher-level cognitive processes. Although means-ends problem solving is typically studied in the context of manual tasks, locomotion can also require infants to discover and coordinate various means to achieve a goal, as when infants identify an alternative sliding position for descending slopes, recognize that a sturdy handrail can augment their balance on narrow bridges, and invent strategies for making a wobbly handrail suffice.

One hallmark of means-ends problem-solving is tool-use. The experiments in which walking infants used handrails as tools for keeping balance illustrate how the acquisition of new locomotor means is rooted in the development of both cognitive and motor abilities (Berger & Adolph, 2003; Berger et al., 2005). Successful tool-use requires infants to master three steps and sequence them into the appropriate order: First, infants must recognize the existence of a gap between their own ability and typical means for achieving a goal. Second, infants must understand that an environmental support—a tool—is available that can serve as alternative means for reaching the goal. Third, infants must implement the tool by modifying their typical means.

In the bridges and handrails studies, the first step in the sequence was based on infants' perception of affordances (or lack of them) for crossing narrow bridges. The third step was rooted in infants' ability to modify their typical walking gait by turning sideways and holding the rail. It was the second step that reflected true means-ends problem-solving. Envisioning a handrail as an alternative means for crossing a narrow bridge meant that infants coordinated several pieces of information about the handrail, the bridge and their own bodies. Thus, developmental changes in cognition can affect infants' motor abilities.

Reciprocally, developmental changes in infants' locomotor skills can affect their cognitive abilities. Both cognitive and motor demands compete for infants' finite attentional resources. There is a limit to how much infants can attend to at one time. When infants' attention is overtaxed by a demanding motor challenge, there is a trade-off between cognition and action—part of performance is sacrificed so that the other part of the task can be carried out (Boudreau & Bushnell, 2000; Keen, Carrico, Sylvia, & Berthier, 2003). As infants' crawling and walking proficiency increases, they can devote less attention to keeping balance and, in turn, can allocate more resources to higher-level cognitive processes.

At 12 months, for example, infants no longer exhibit the A-not-B error. After watching an experimenter move a target to a new location, they can inhibit the prepotent response of reaching for the object in the same location where they had retrieved it several times on previous trials. By 12 months, reaching is highly practiced and demands little in terms of cognitive resources. Walking, however, is a different story. Upright balance is still precarious in challenging situations, and infants must devote their attentional resources to solving the motor problems. Thus, in a locomotor version of the A-not-B task, 13-month-old infants repeatedly moved to one location, A, and then were encouraged to go to a second location, B (Berger, 2004). On the B trial, infants inhibited the urge to return to the A location when motor demands were low (walking over flat ground to reach the goal), but the same infants perseverated when motor demands were high (descending a small staircase to the goal). What matters is not the task per se, but rather how much cognitive capacity is required to perform it. Twelve-month-old infants no longer perseverate on a manual search task where they reach for a hidden object because they are expert reachers (e.g., Diamond, Prevor, Callender, &

Druin, 1997). In contrast, 13-month-olds do perseverate on a locomotor task on which they are novice stair climbers (Berger, 2004).

Conclusion

These days, it is popular to resurrect Piaget's old idea that motor skill acquisition influences the development of perception and cognition. We have no doubt that Piaget was on the right track. New motor skills provide infants with new opportunities for learning about the self and the environment, and the relations between the two. Stance and mobility take so many different forms in infancy—from sitting on a caregiver's knee to slithering under the coffee table—that the only common denominator may be the involvement of the whole body. The whole body is involved in detecting affordances for locomotion, and finding the means to create new affordances with a tool.

The reciprocal developmental relationship is also true: Developments in perception and cognition can facilitate development of locomotor action. Perception and cognition are integral to independent mobility. For infants, getting down a slope or stair or across a bridge is an opportunity to perceive changing affordances and an invitation to means-ends problem solving. We can best see the relations between perception, cognition, and action when we observe infants engaged in real locomotion in all its manifold forms, through a cluttered environment, with variable goals.

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